Simulating the Universe

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UCB

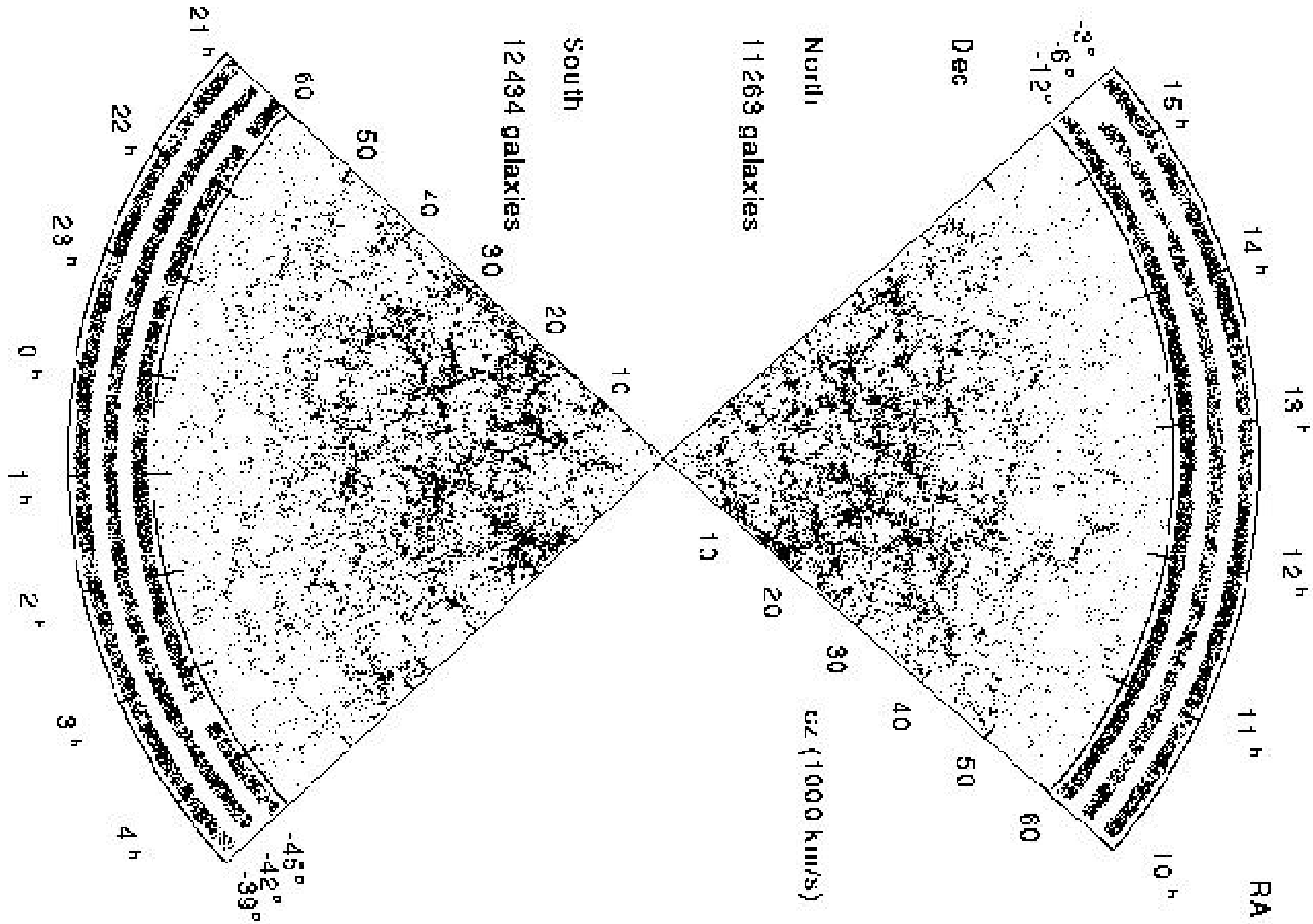
Outline

- Overview of cosmology
- The role of simulations
- Physics and algorithms
- Some examples
- The future …

Cosmology overview

- When we observe the universe we see a wealth of structure on essentially all scales.
  - Stars cluster into galaxies
  - Galaxies into clusters of galaxies,
  - Clusters into super-clusters
  - And so on.

Large-scale structure in the distribution of galaxies

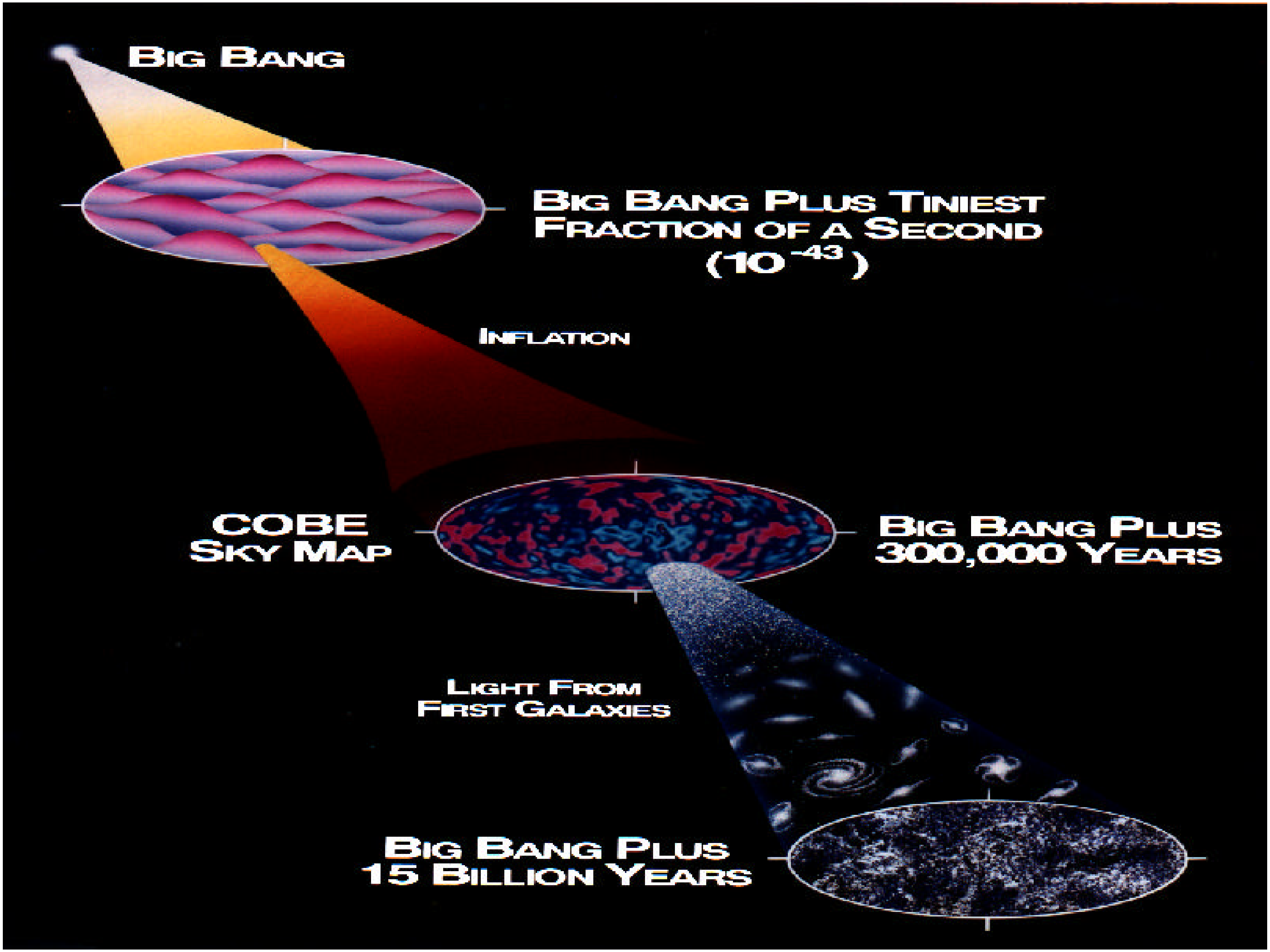



THE RESEARCH CONTINUES...
DO COSMOLOGISTS FORM CLUSTERS?...
...AND DO THE CLUSTERS FORM SUPERCLUSTERS?
S. Harris

The most beautiful story in Physics:

- We believe that these cosmic structures had their origins in quantum fluctuations generated during the early universe.
- These fluctuations were amplified by gravitational instability.
  - we see them as tiny fluctuations in the temperature of the relict radiation left over from the big bang (t~300,000 yr),
  - … and as correlations in the distribution of galaxies today ($t \sim 10^{10}$ yr).

The Big Picture



Gravity is the Engine of Growth

- The dominant force is gravity, the dominant component is (collisionless, non-interacting) “dark matter”.
- On scales <1 Mpc gas pressure forces become increasingly relevant.
- Galaxies form in dark matter halos, but their properties are dominated by gastrophysics.

Evolution of structure

… courtesy V Springel

QuickTime™ and a Cinepak decompressor are needed to see this picture.

The role of simulations in cosmology …

- Many problems in astrophysics lack the symmetries that generally allow analytic solution. A full 3D numerical treatment is required.
- Numerical simulations play a key role in cosmology.
- In cosmology know both the PDEs *and* the initial conditions!
- Ab initio calculations are possible (in principle)

We are using simulations to …

- Understand the evolution of galaxy clustering (DEEP2, VIRMOS, …)
  - Mock galaxy catalogues, galaxy formation models.
- Make predictions for weak lensing surveys.
  - Model non-linear evolution of DM.
  - Affects high-z supernovae, constrains DE!
- and the Sunyaev-Zel'dovich effect
  - Simulated observations for experiments.
  - Basic theory.
- Quantify merger rates of galaxies and black holes
  - Main gravity wave source for LIGO, LISA, …
- Elucidate the structure of our dark matter halo
  - Direct detection experiments
- Study small-scale structure (Ly-α forest)
  - Strong limits on DM properties (& dark energy?)

Types of physics included …

- Gravity
  - All cosmology codes have this! Dominates the forces above the scale of galaxies.
- Hydrodynamics
  - Adiabatic physics
  - Cooling
  - Star “formation” and feedback
- Magnetic fields (MHD)
  - Not so common in cosmology.
- Radiative transfer
  - Still early days …

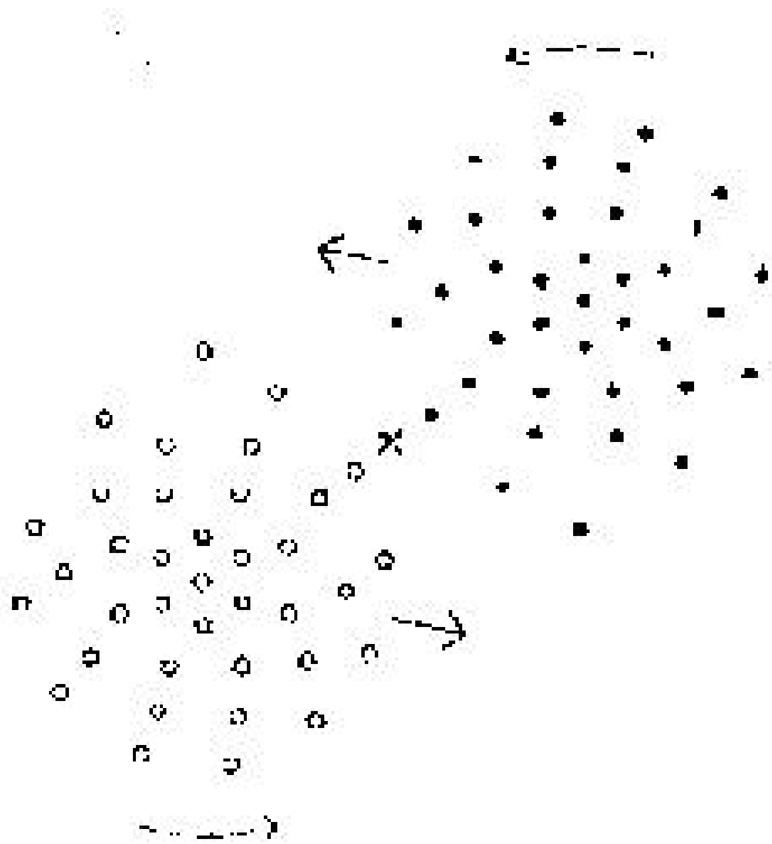
Gravity: the N-body method

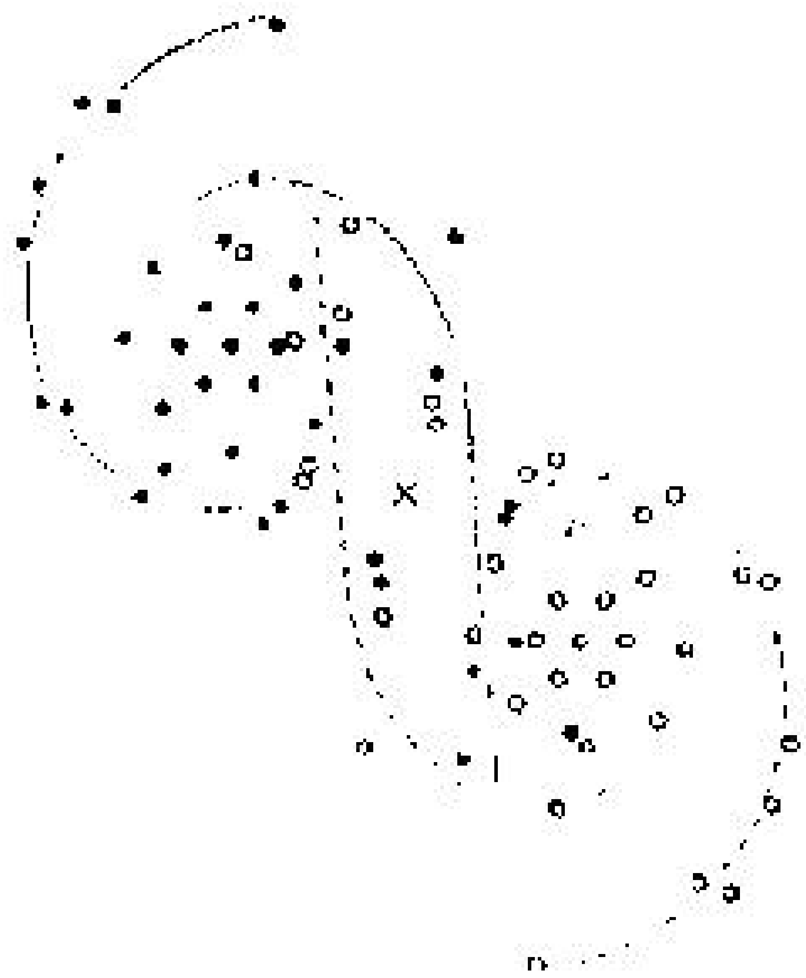
- Original N-body work was for stellar systems (a true "N-body problem").
- Taken over to cosmology – change in emphasis: now modelling DM dominated systems as a **fluid**.
- Need to solve the *Vlasov Equation* or collisionless Boltzmann equation…

Monte-Carlo

- Solve this 6N-dimensional equation using Monte-Carlo techniques.
- Sample phase space with a set of N>>1 “superparticles”.
- If superparticles follow characteristics of the Vlasov equation (in expanding universe) then distribution function is correctly evolved.
- It’s not about orbits, it’s about N!!

The first N-body simulations …

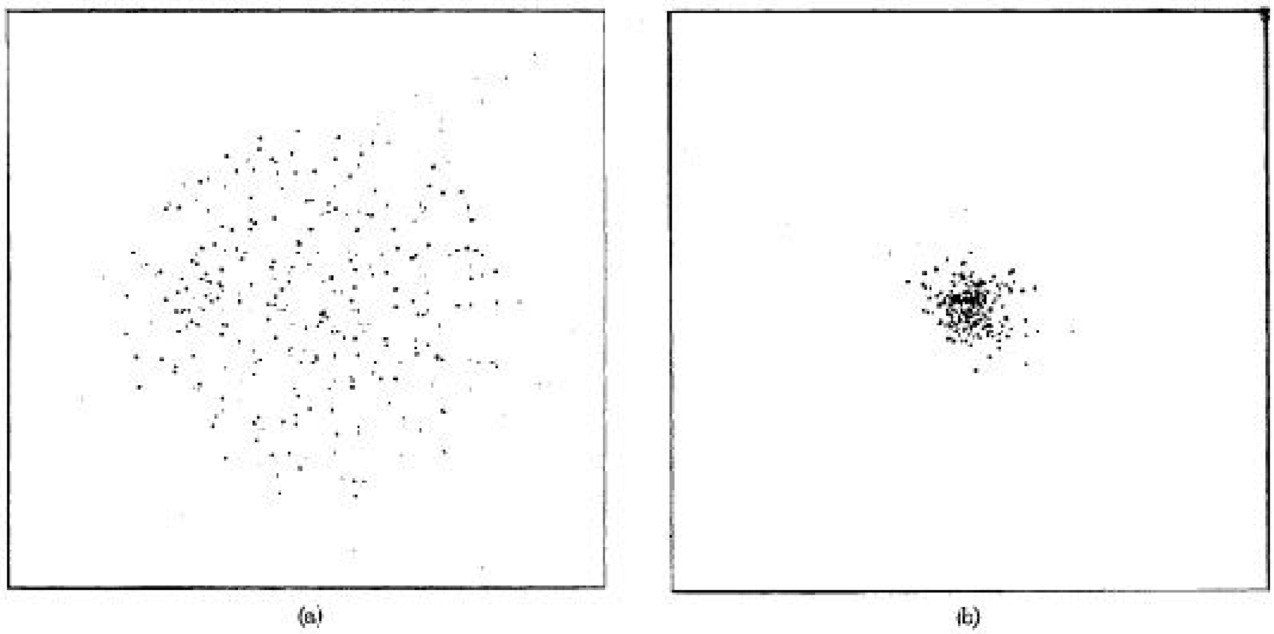


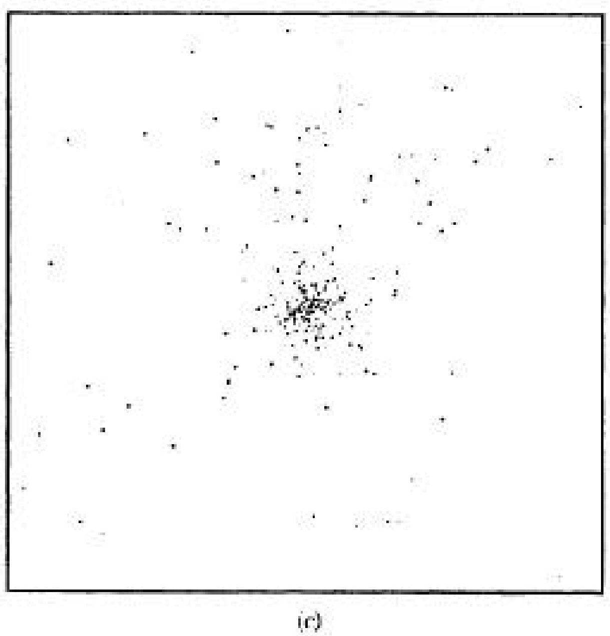


Erik Holmberg (1941)

2D, N=74

… in cosmology …



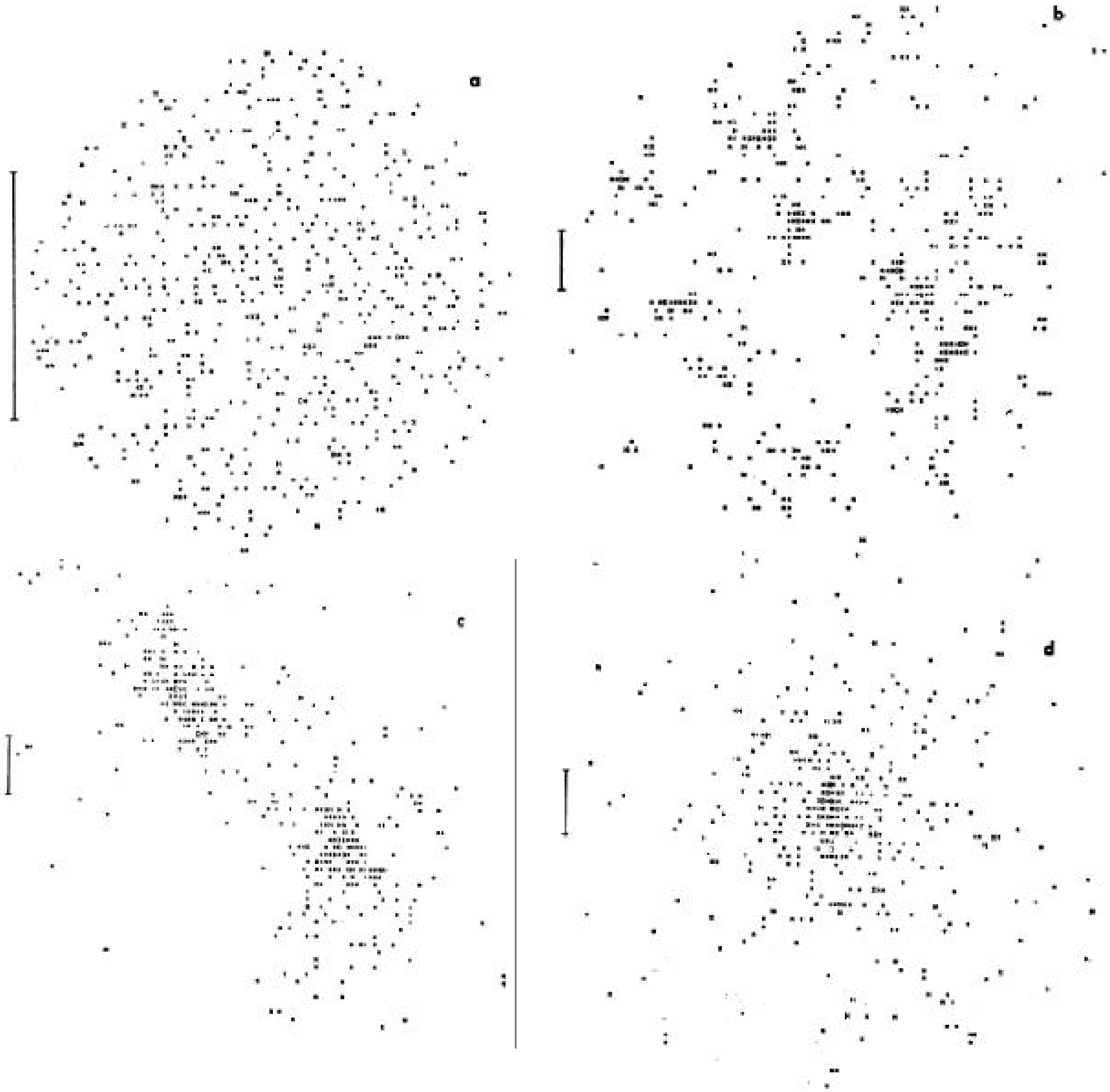


Jim Peebles (1970)

FIG. 1. Model 1 positions: (a) initial positions, $t=2.8$ b.y.; (b) $t=5.6$ b.y.; and (c) $t=8.4$ b.y.

N=300 (3D)

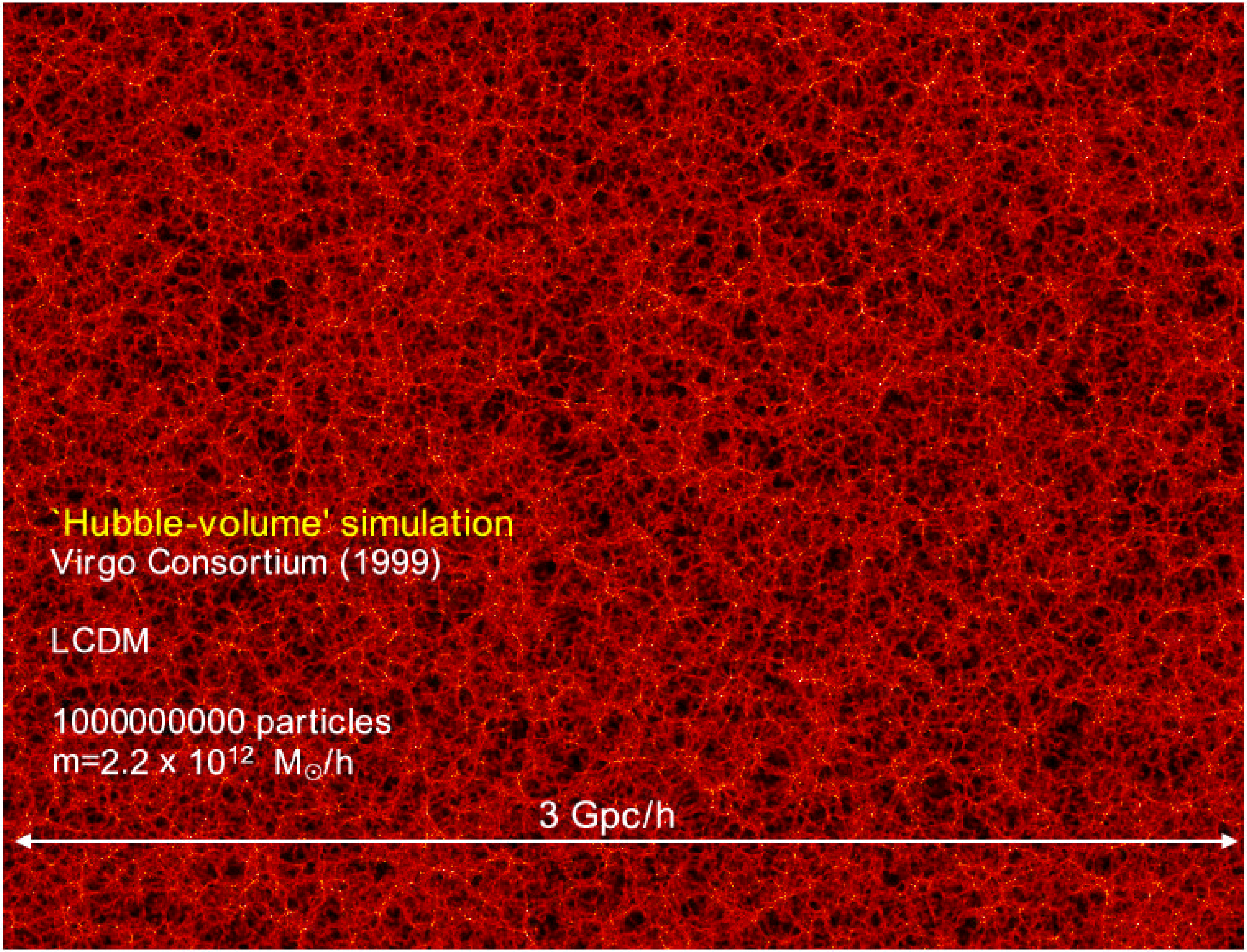
… with ‘realistic’ ICs:



Simon White (1976)

N=700 (3D)

The state of the art …



The approach

- Lay down particles with positions and velocities determined by early universe theory.
  - Can be random realization or
  - Constrained realization
- Evolve positions and velocities (using low order integrator) using Newton’s laws (generalized to an expanding universe).
- Smooth forces to reduce 2-body scattering.

Computing the forces

Direct summation	O(N^2) [Special hardware]	Practical for $N<10^4$
Particle mesh	O(N logN)	Uses FFTs to invert Poisson equation.
Tree codes	O(N logN)	Multipole expansion.

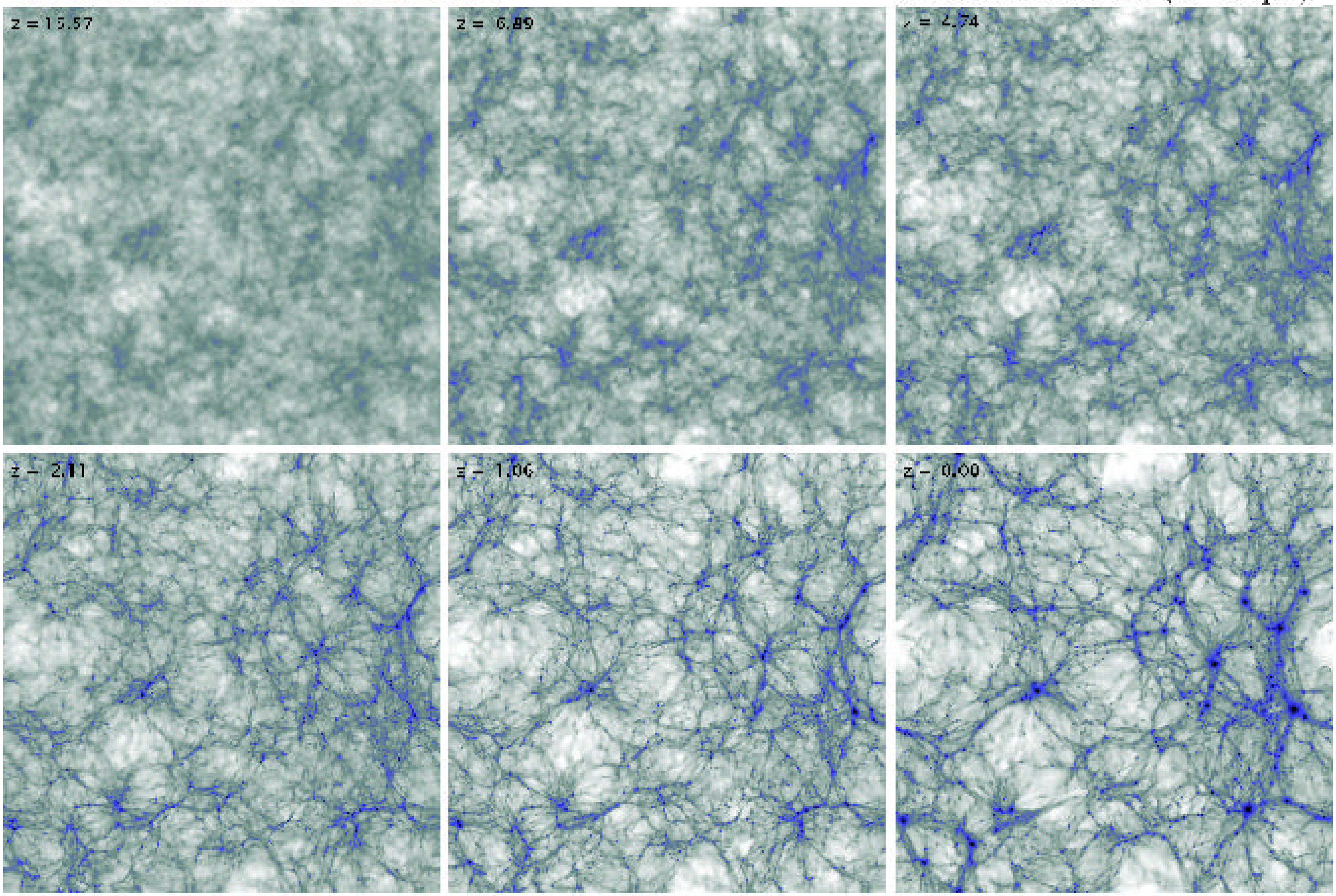
All modern methods are hybrids of these!

Large-scale structure arises from Gaussian initial conditions seeded by inflation

$\Lambda\mathrm{CDM},\ N = 2 \times 224^3$

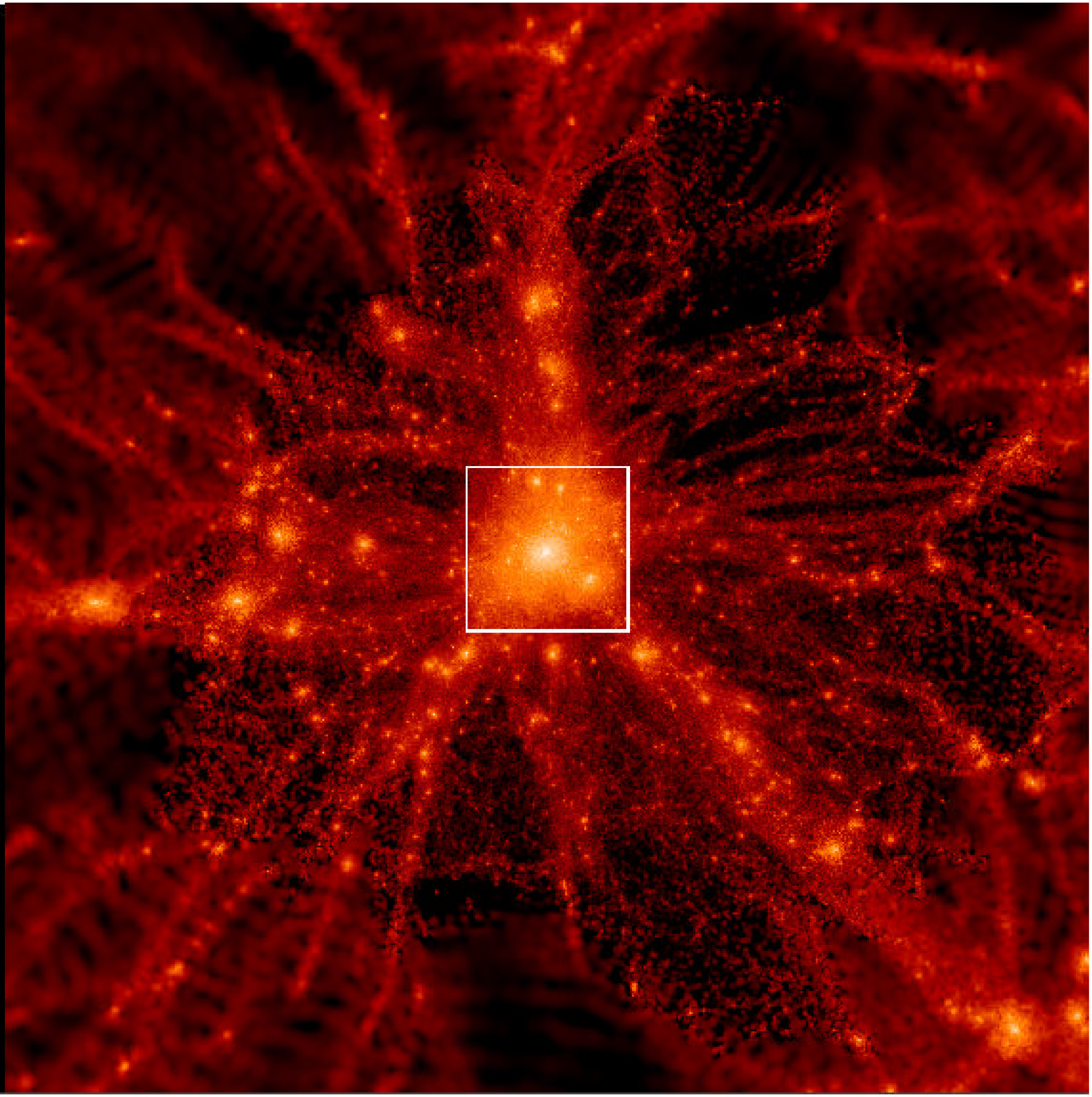
$134 \times 134 \times 22.3\ (h^{-1}\mathrm{Mpc})^3$

EVOLUTION OF STRUCTURE



Springel, Hernquist & White (2000)

Zooming in on a cluster of galaxies



Springel et al. (2000)

Zooming in
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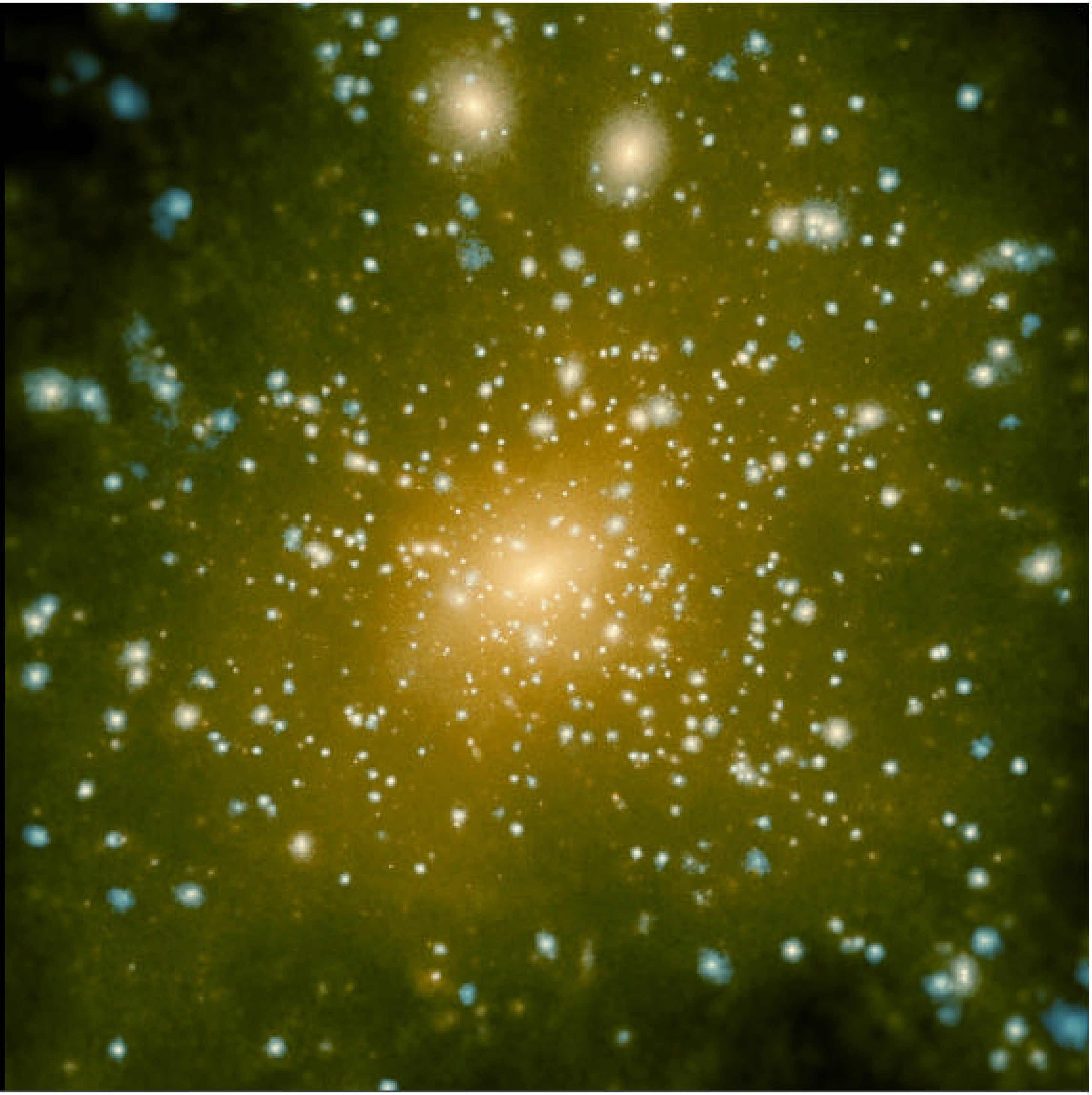
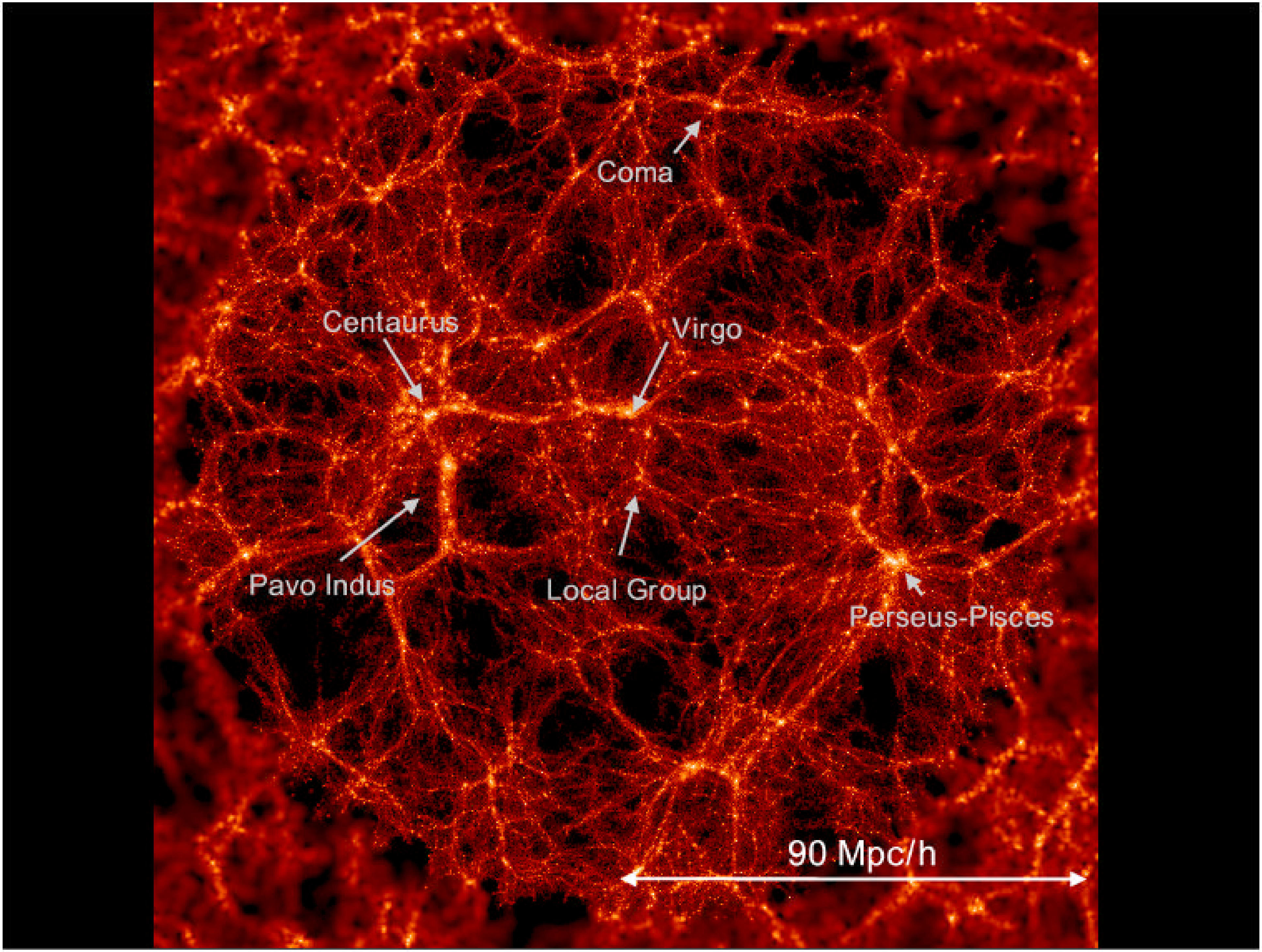
of galaxies



Springel et al. (2000)


Coma
Centaurus
Virgo
Pavo Indus
Local Group
Perseus-Pisces
90 Mpc/h

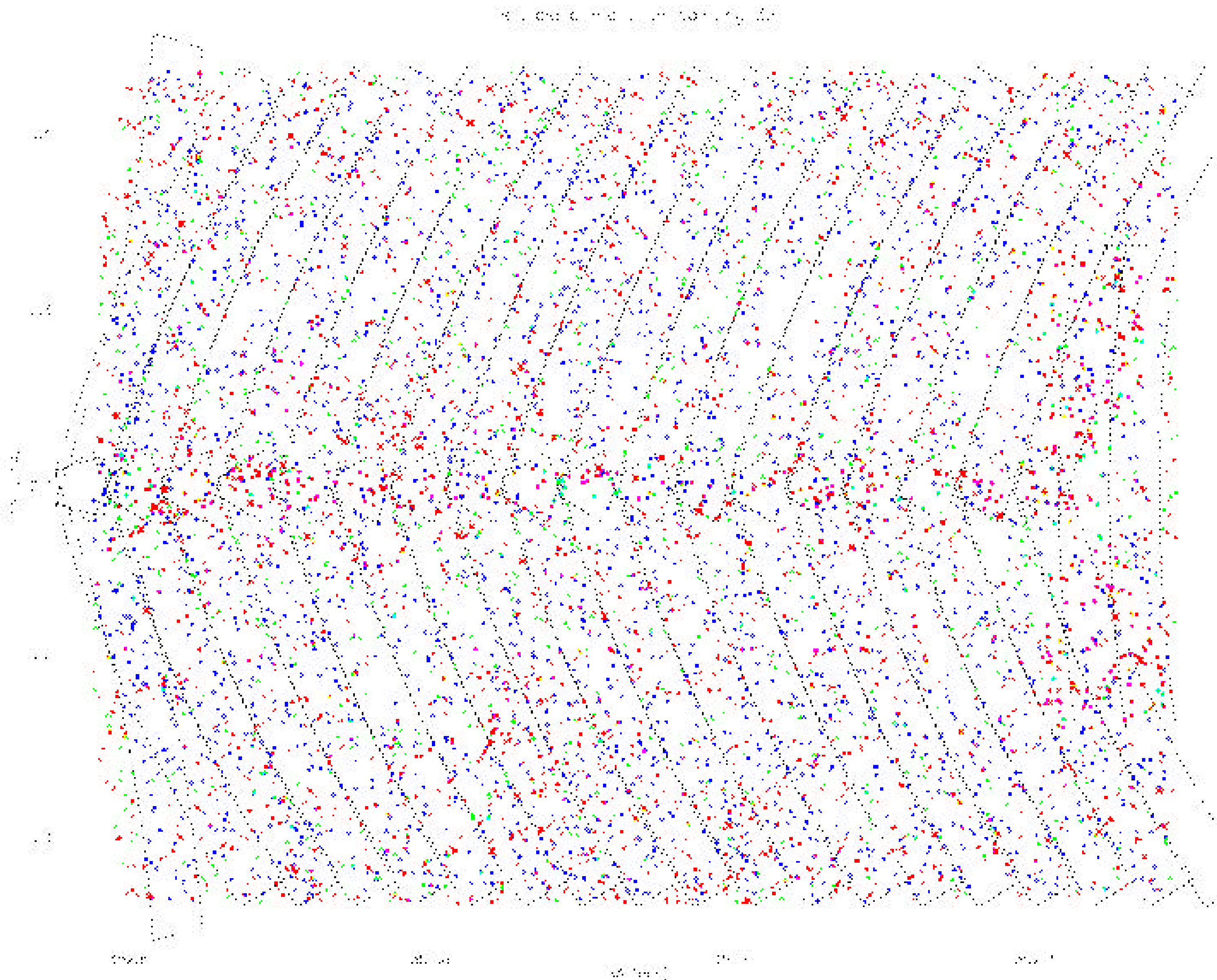
Applications of large-scale simulations

- Simulations are now routinely used to analyze almost all situations in cosmology.
- Four examples
  - Mock redshift surveys
  - Gravitational lensing
  - Sunyaev-Zel'dovich effect(s)
  - Ly-α forest

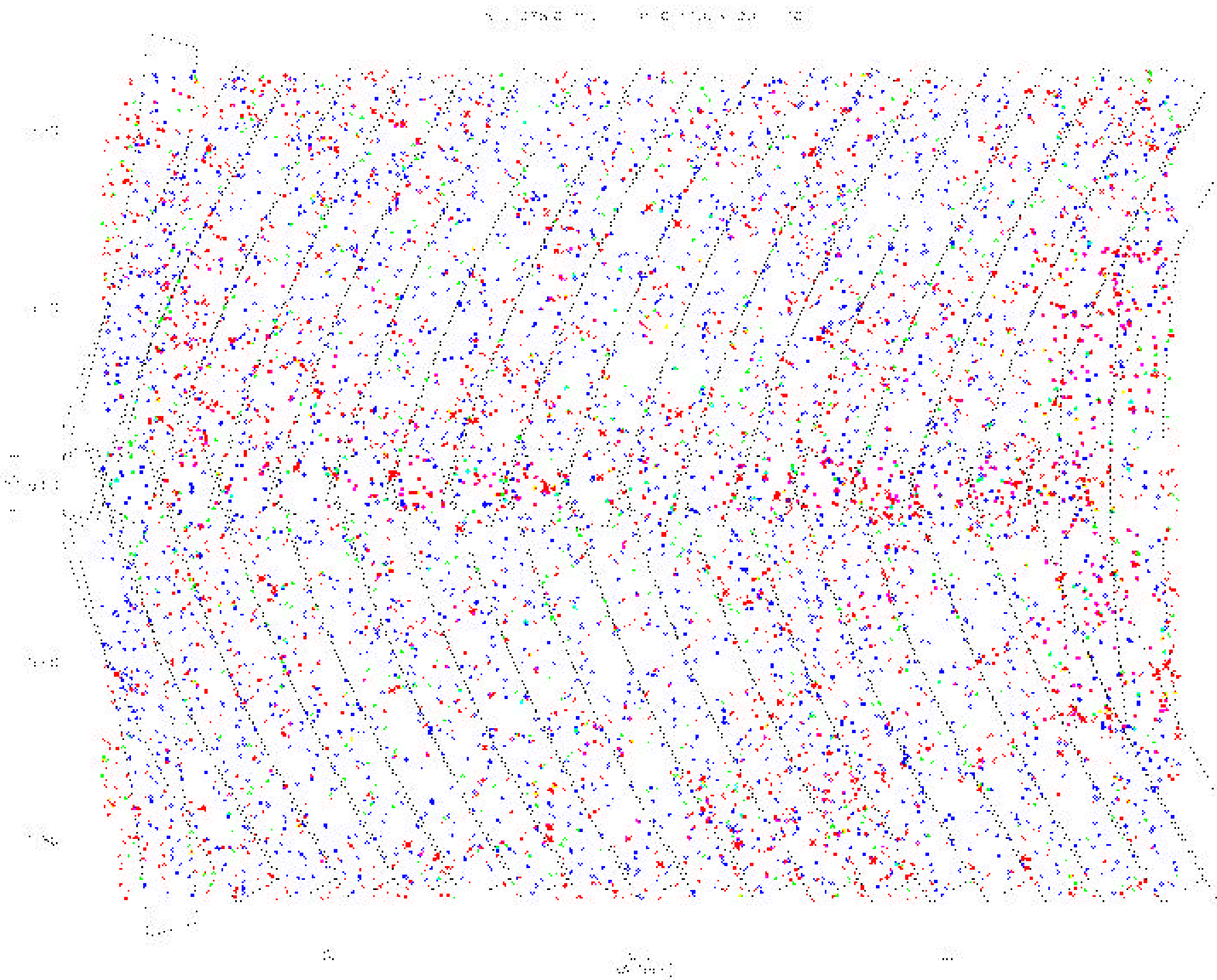
Modern redshift surveys

- Modern redshift surveys routinely make use of mock catalogues to
  - Design the survey strategy.
  - Tune and calibrate algorithms.
  - Correct data products for survey artifacts.
- Example: the DEEP2 survey…

Mock DEEP2 surveys

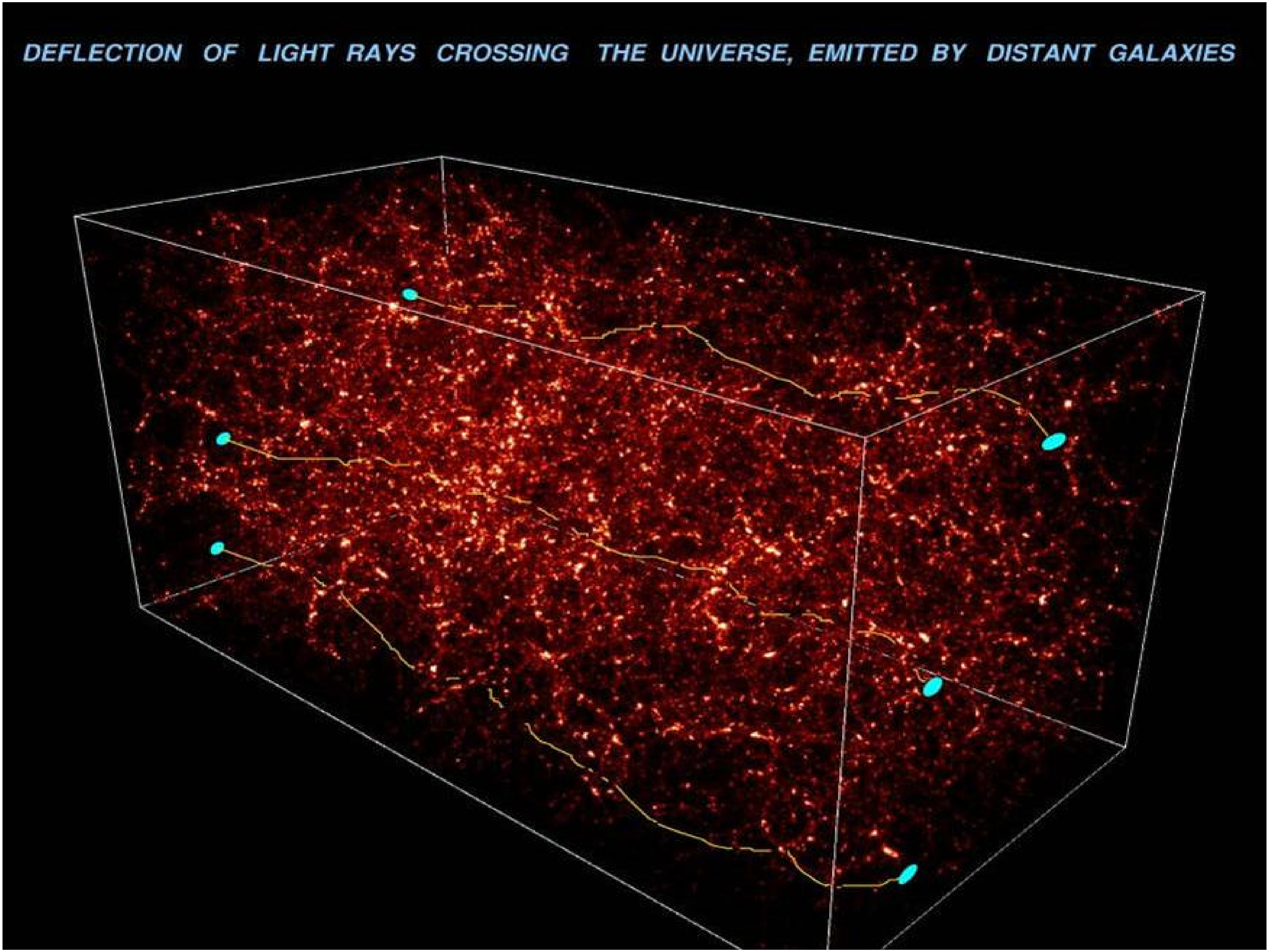


Mock DEEP2 surveys



Ways to find: Clusters of Galaxies

- Largest structures in the universe: mountains of the cosmos!
- Provided first evidence for dark matter.
- In a universe wherein structure formed hierarchically
  – Small things form first and merge or accrete other small things to get bigger
- the largest objects are special.
- Most sensitive to our modelling assumptions.


DEFLECTION OF LIGHT RAYS CROSSING THE UNIVERSE, EMITTED BY DISTANT GALAXIES

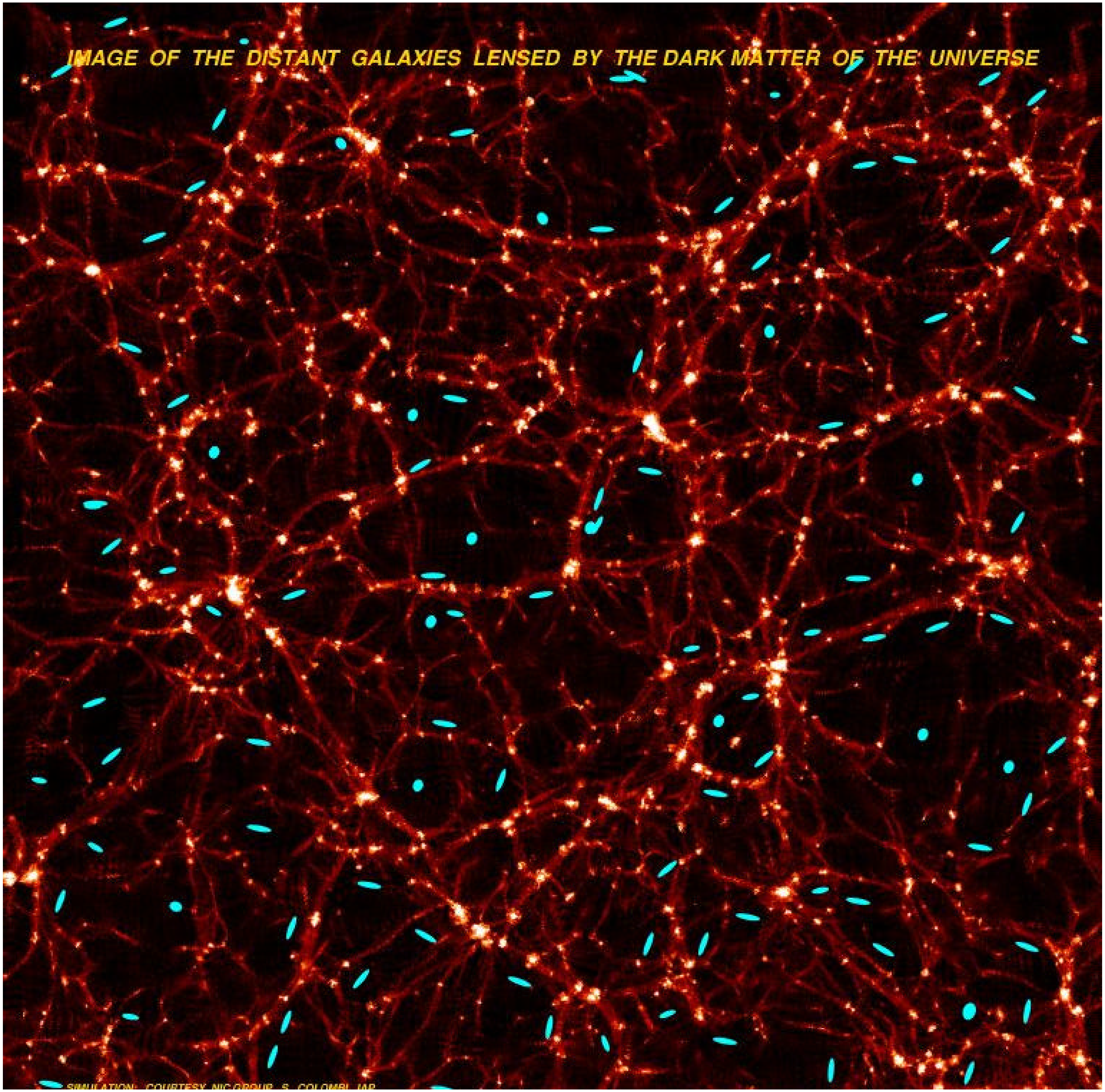
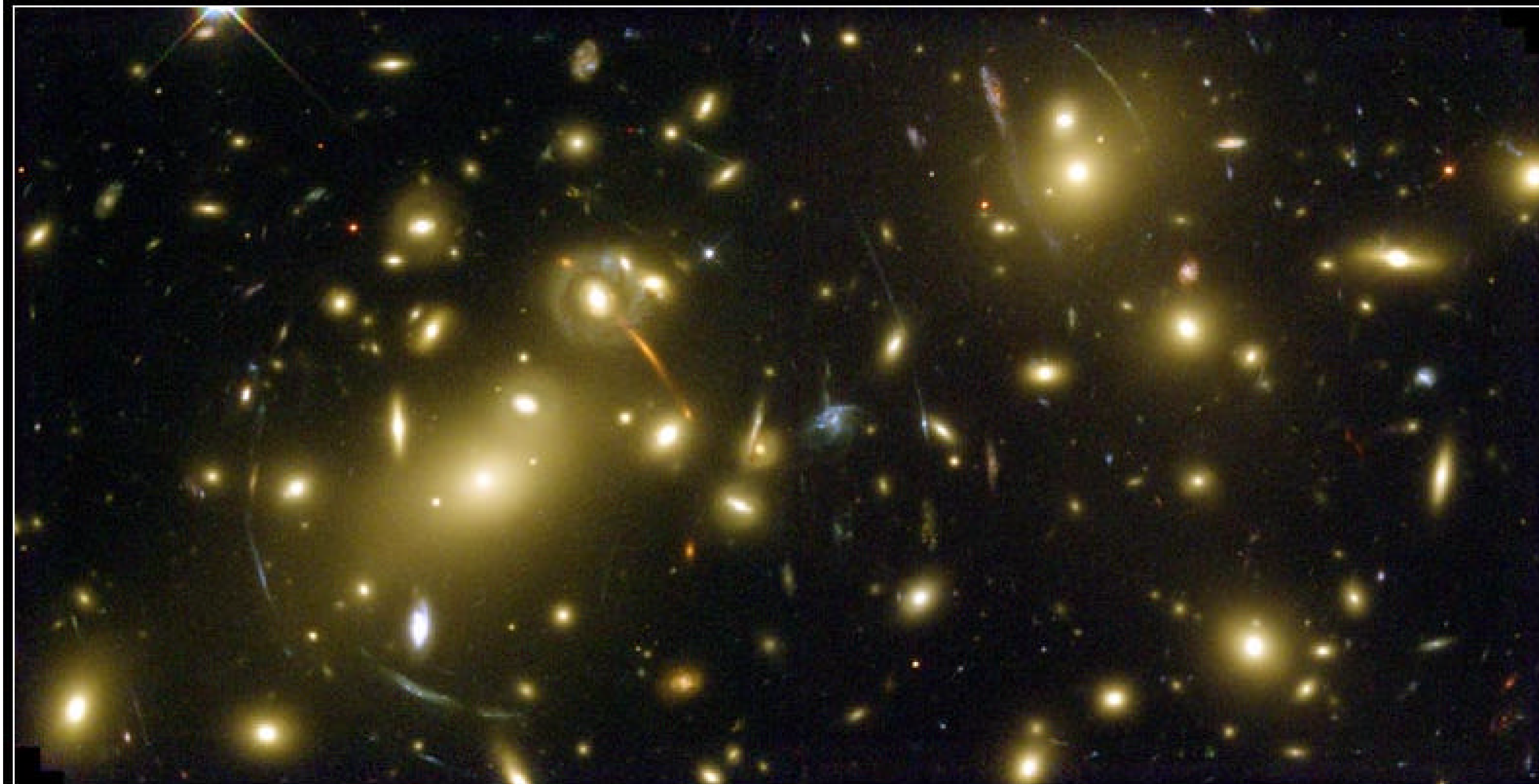


IMAGE OF THE DISTANT GALAXIES LENSED BY THE DARK MATTER OF THE UNIVERSE
SIMULATION: COURTESY NIC GROUP, S. COLOMBI, IAP

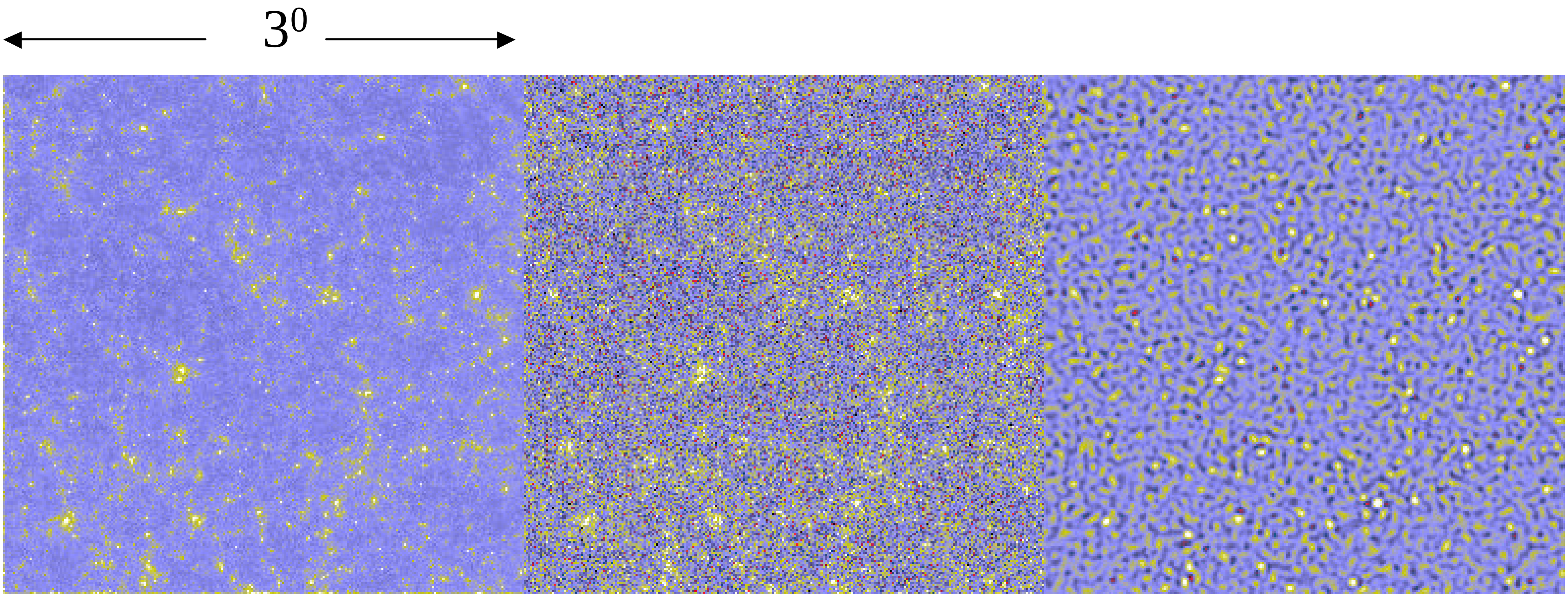
Gravitational lensing in A2218



Galaxy Cluster Abell 2218 **HST • WFPC2**

NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08

Weak lensing maps: simulations



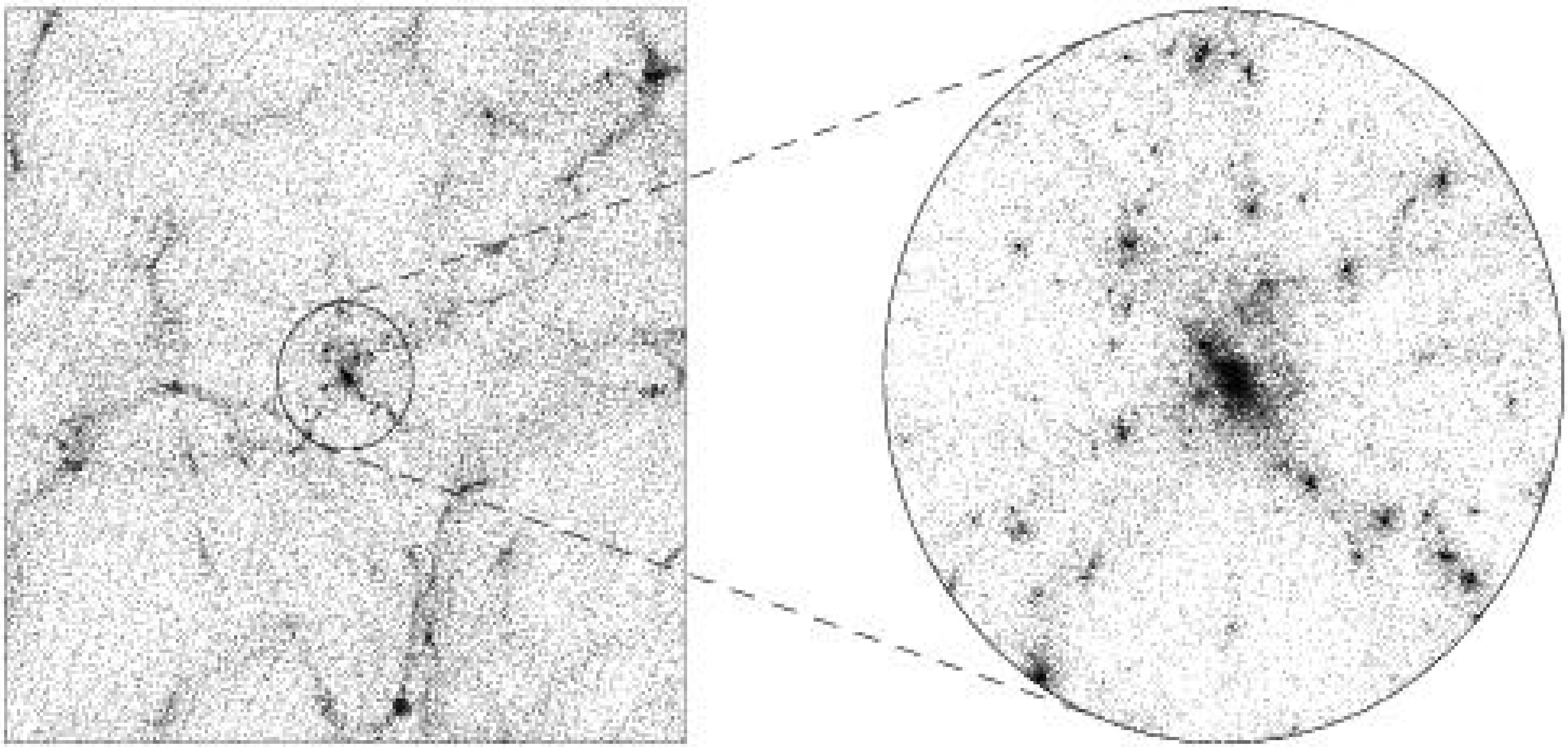
Raw convergence map – roughly projected mass.

+ noise from shear reconstruction

Filtered

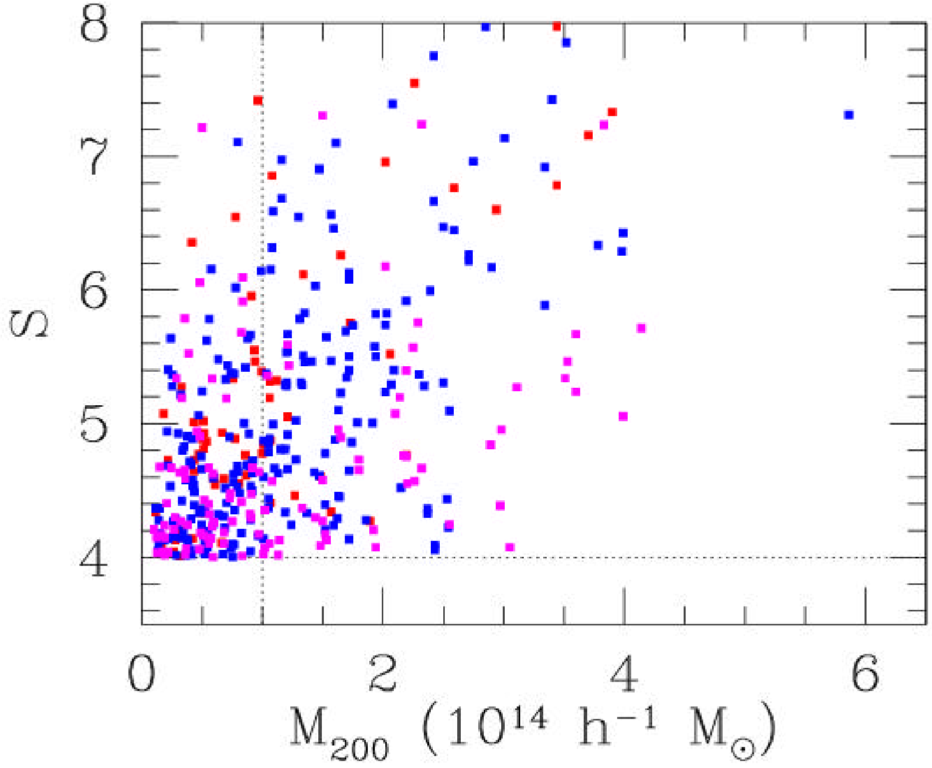
White, van Waerbeke & Mackey (2002)

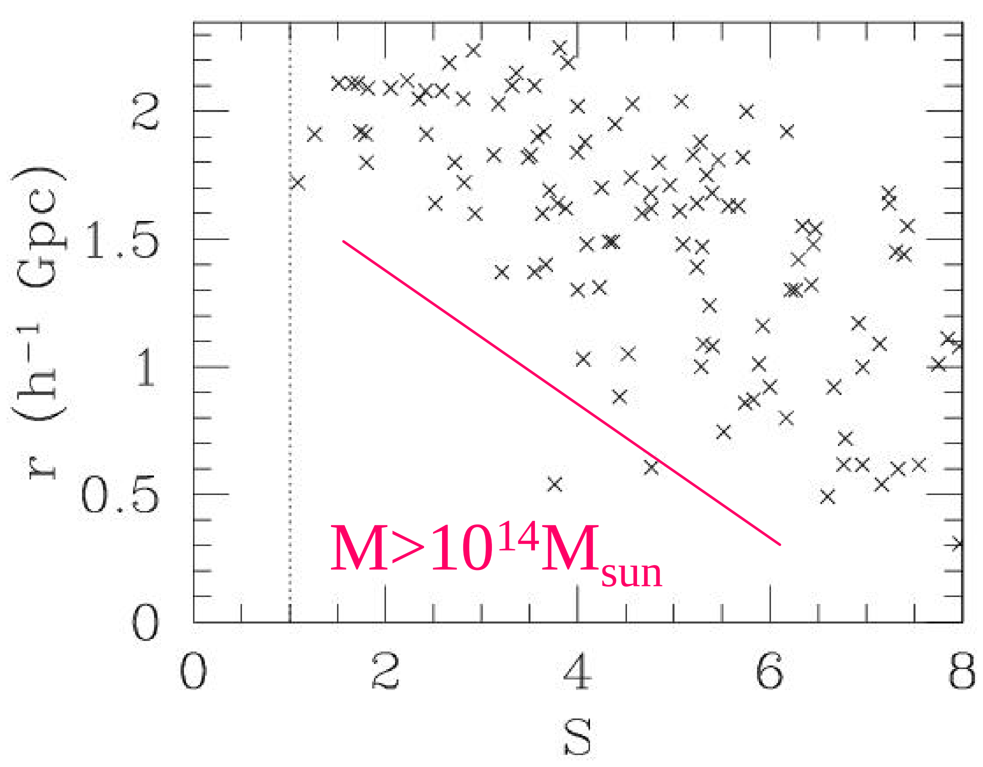
Clusters are part of large-scale structure



Metzler, White & Loken (2001)

Lensing scatterplots

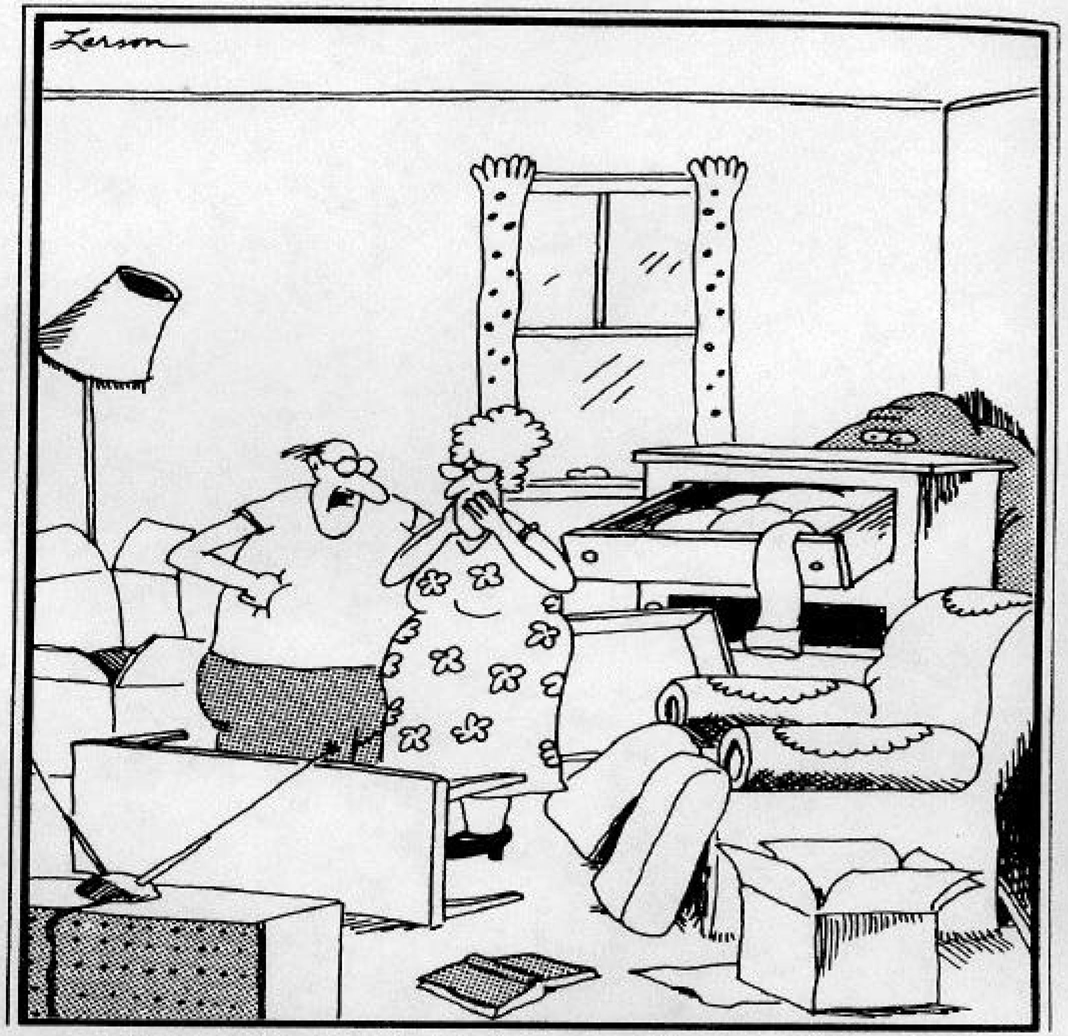




Large scatter means low completeness

At fixed mass the threshold is distance dependent!

Clusters can "hide" among the projected large-scale structure.



"Now calm down, Barbara. ... We haven't looked everywhere yet, and an elephant can't hide forever."

Adding gas …

- Beyond gravity – hydrodynamics!
- Two main approaches
  - Grid based (Eulerian)
    - Mostly regular grids, often with refinement
    - PPM or TVD schemes
  - Particle based (Lagrangian)
    - SPH, often with adapative smoothing
- Gravity is always done with particles

The Sunyaev-Zel'dovich Effect(s)

- Compton scattering of CMB photons by hot gas along line-of-sight.
- Upscattering of CMB photons leads to ~mK temperature decrements in CMB at low frequency.
- Signal dominated by clusters of galaxies.
- Measures total internal energy of cluster.
- Dominant secondary anisotropy.
- Independent of redshift!

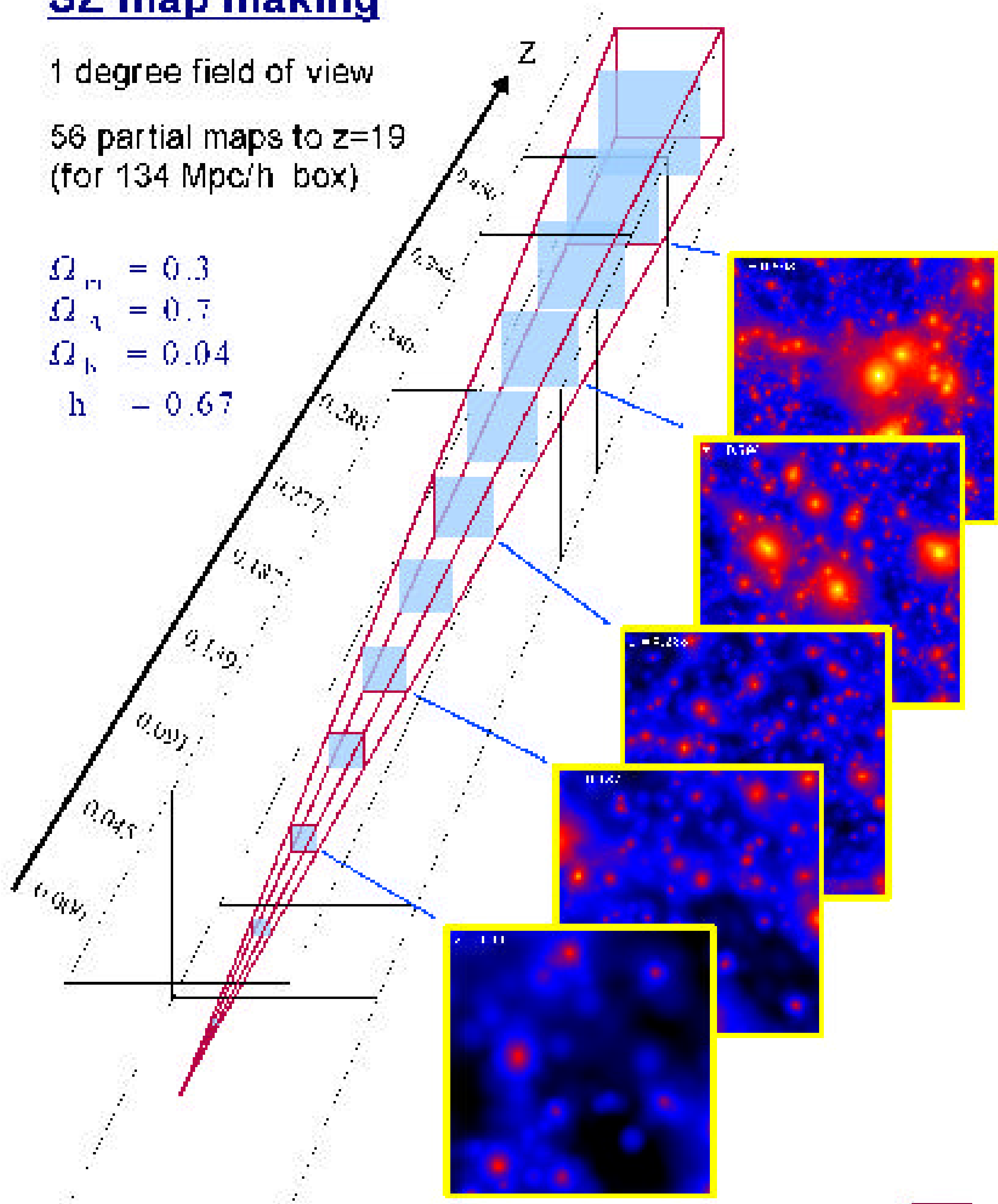
New observational handles …

Name	Type	Beam (arcmin)	Cluster Yield
ACBAR	Bolo	4	Few
Bolocam	Bolo	1	10’s
SZIE	HEMT	1	100’s
CBI	HEMT	4	100’s
AMI	HEMT	1	100’s
Amiba	HEMT	1	100’s
APEX	Bolo	0.75	5,000
SPT	Bolo	1	20,000
Planck	Bolo	5	10,000
ALMA	HEMT	--	--

Simulations with adiabatic hydrodynamics trace shock heating of gas in the IGM and in halos

RAY-TRACING CAN BE USED TO OBTAIN PREDICTIONS FOR SECONDARY ANISOTROPIES OF THE CMB

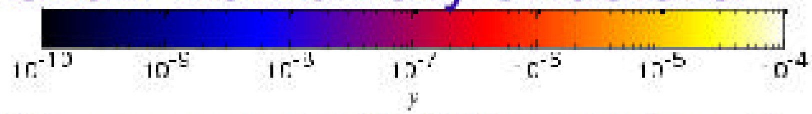
SZ map making

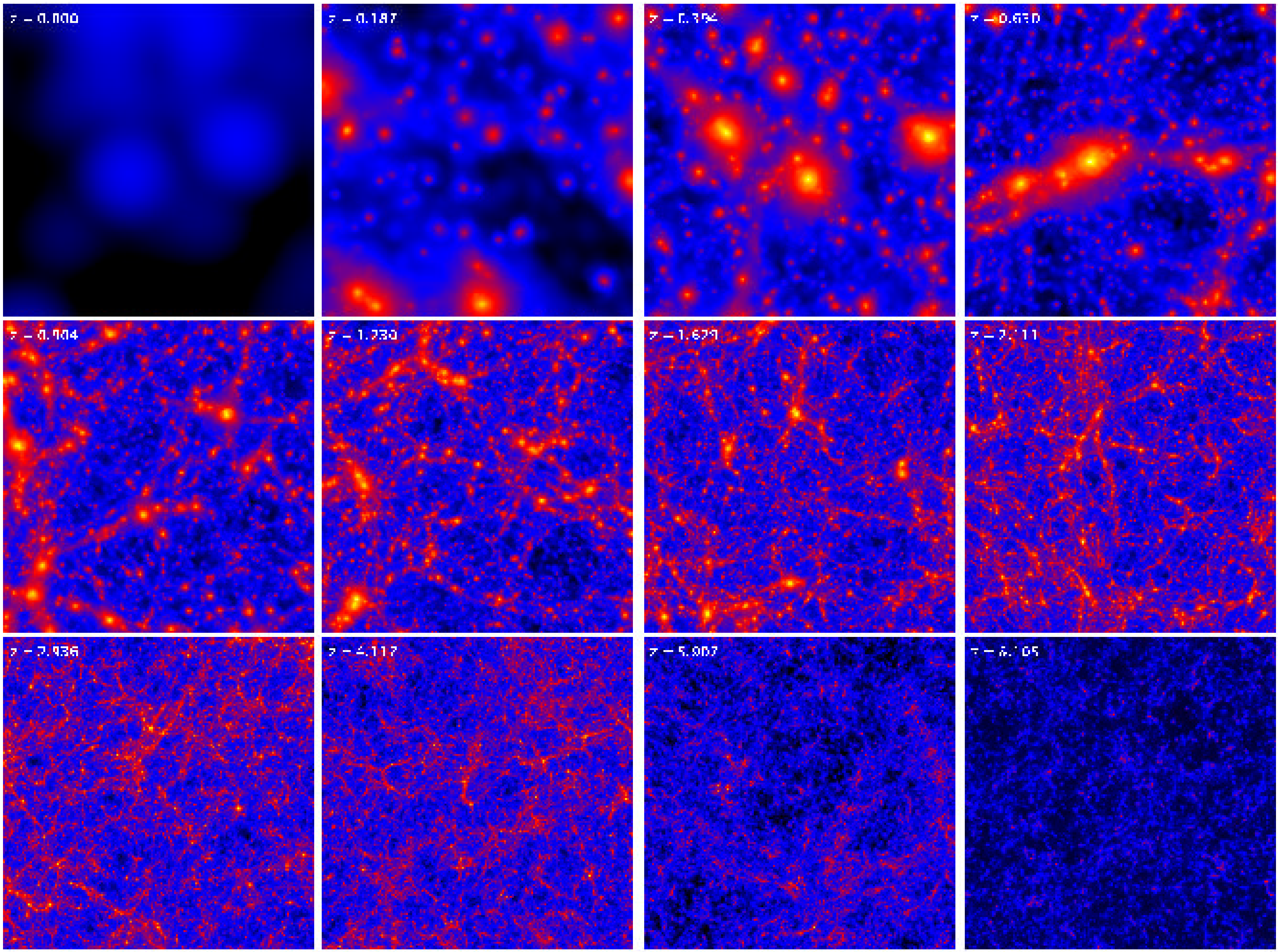


V. Springel, M. White & L. Hernquist (2000)

Partial maps of thermal SZ-effect show filamentary structure

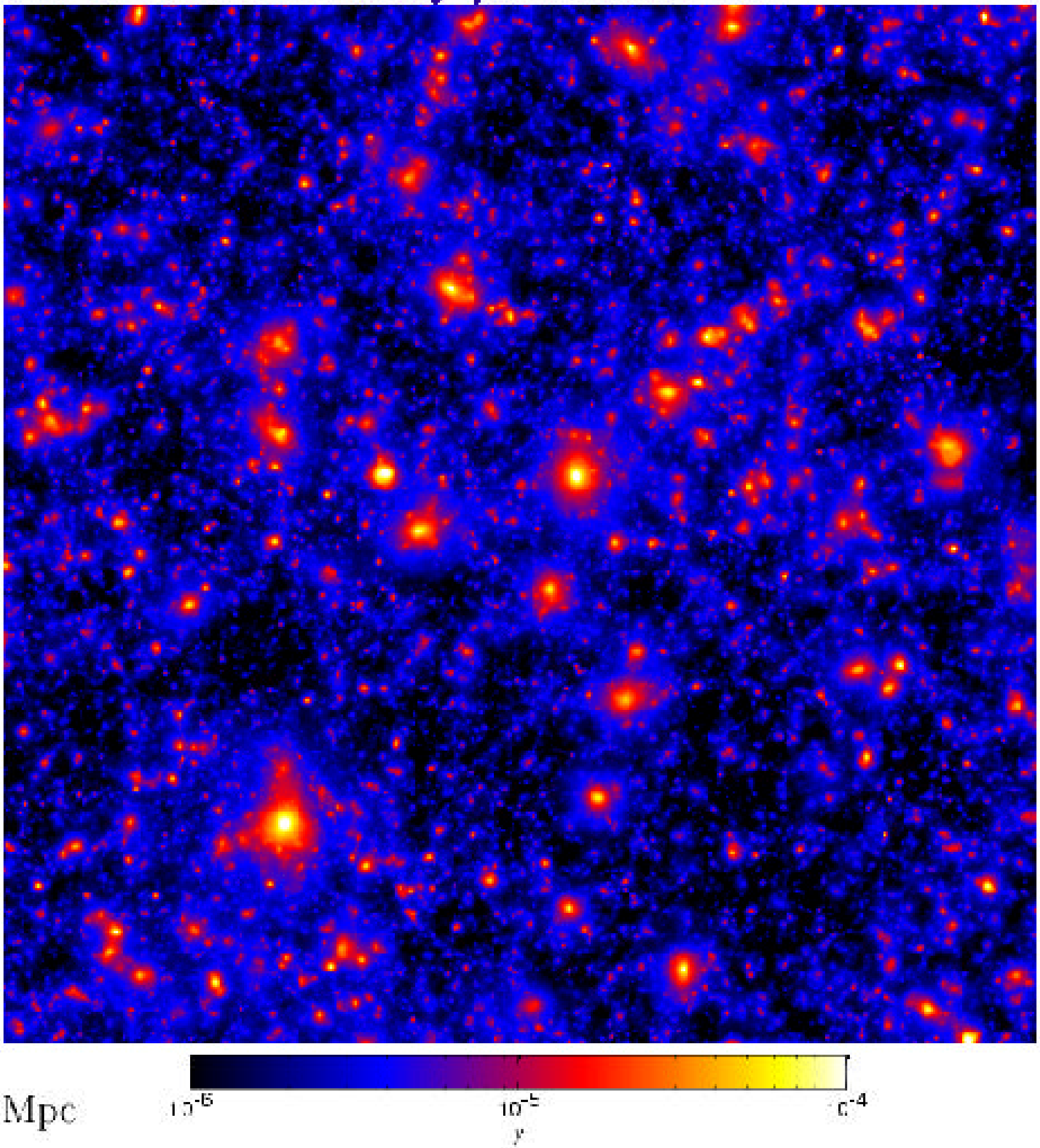
MAPS OF THERMAL SZ-EFFECT





The thermal SZ effect is dominated by point sources

COMBINED MAPS

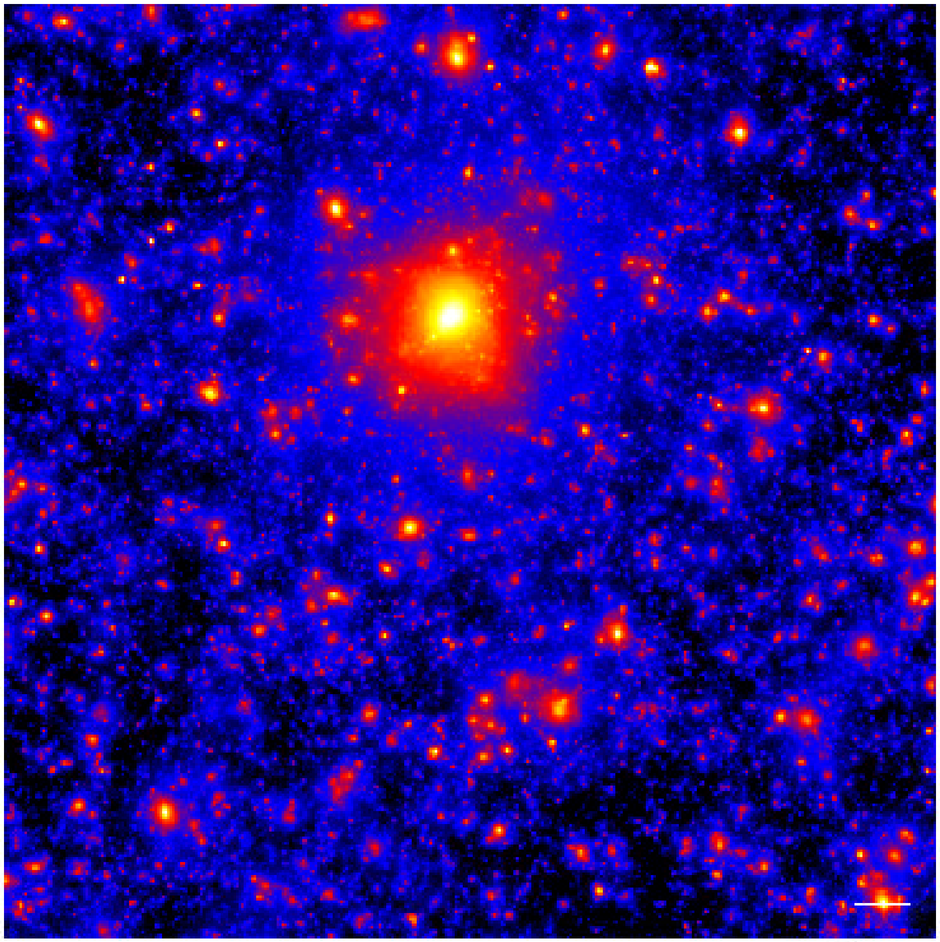


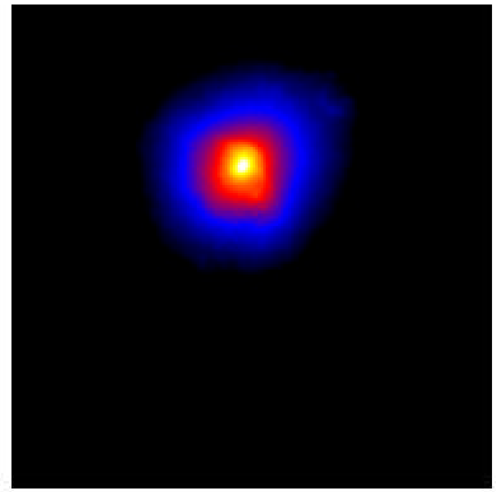
$1^\circ \times 1^\circ$ field, ΛCDM

$N = 2 \times 224^3$, $L = 134\, h^{-1}$Mpc

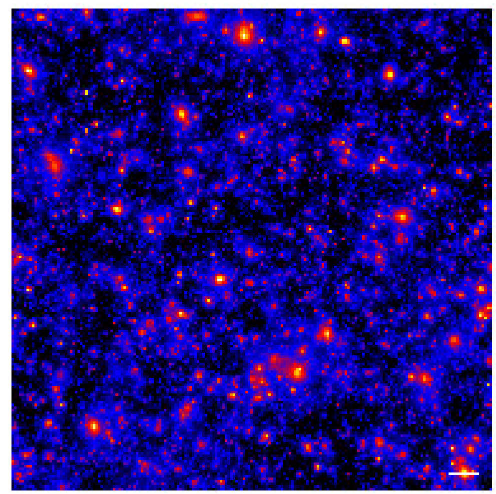
Nearby clusters are huge SZ sources on the sky

A FIELD WITH A NEARBY CLUSTER

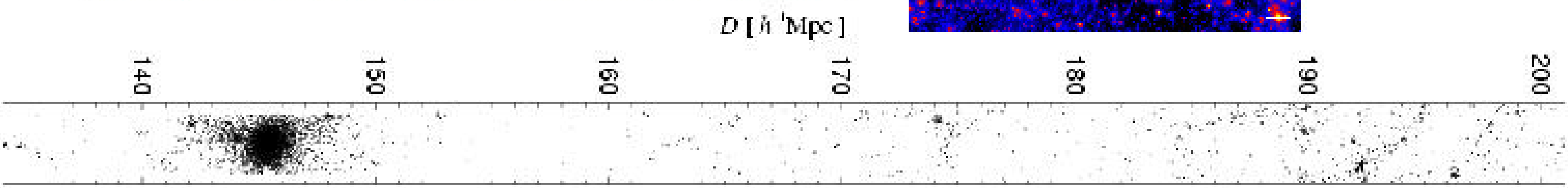




partial map
containing
the cluster

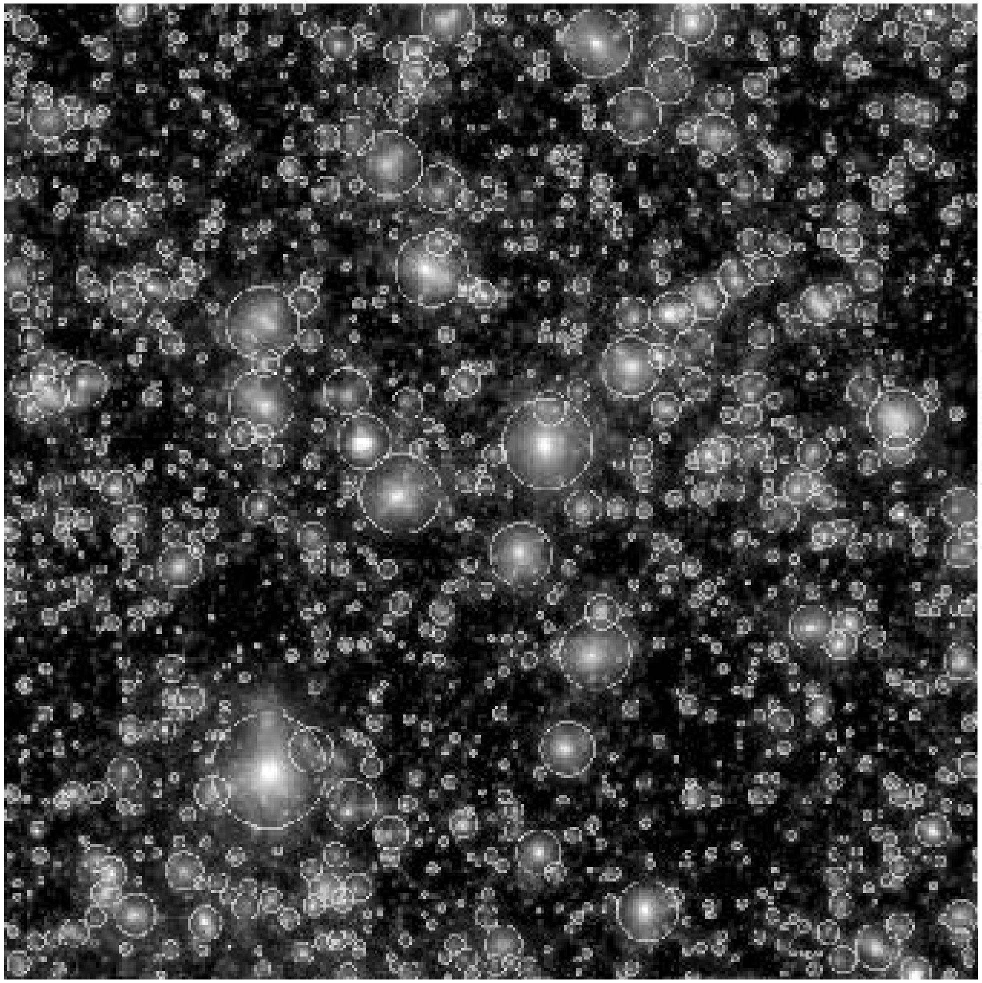


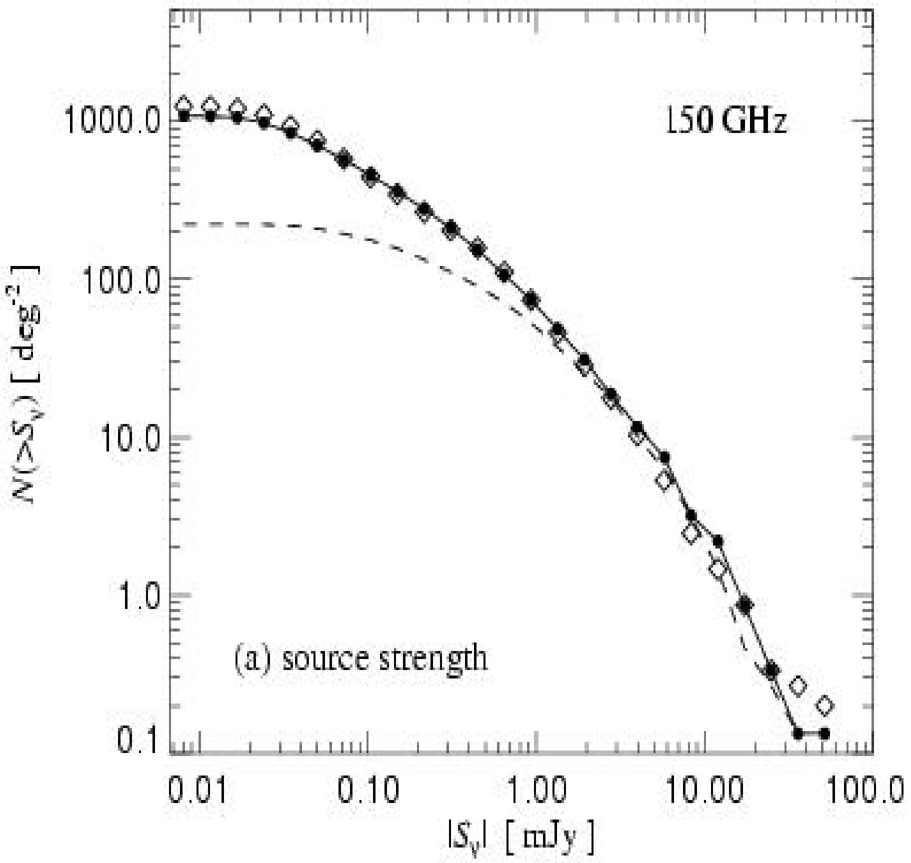
all partial
maps in the
fore- and
background



Probing massive halos …

Sources found with Sextractor



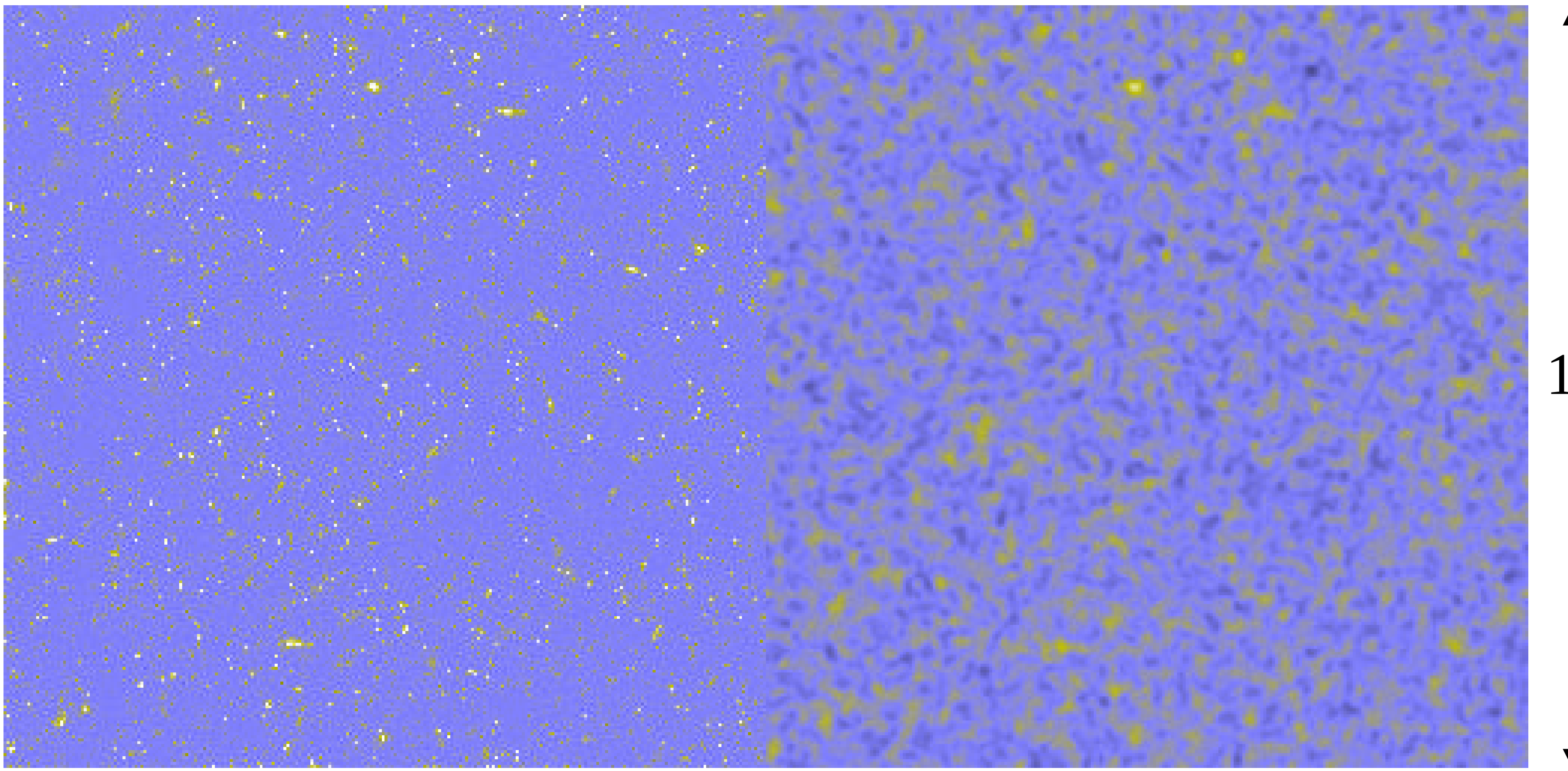


1º

Typical size ~1´

An all-sky survey for massive clusters: *Planck*?

SZ only   SZxbeam+40μK noise

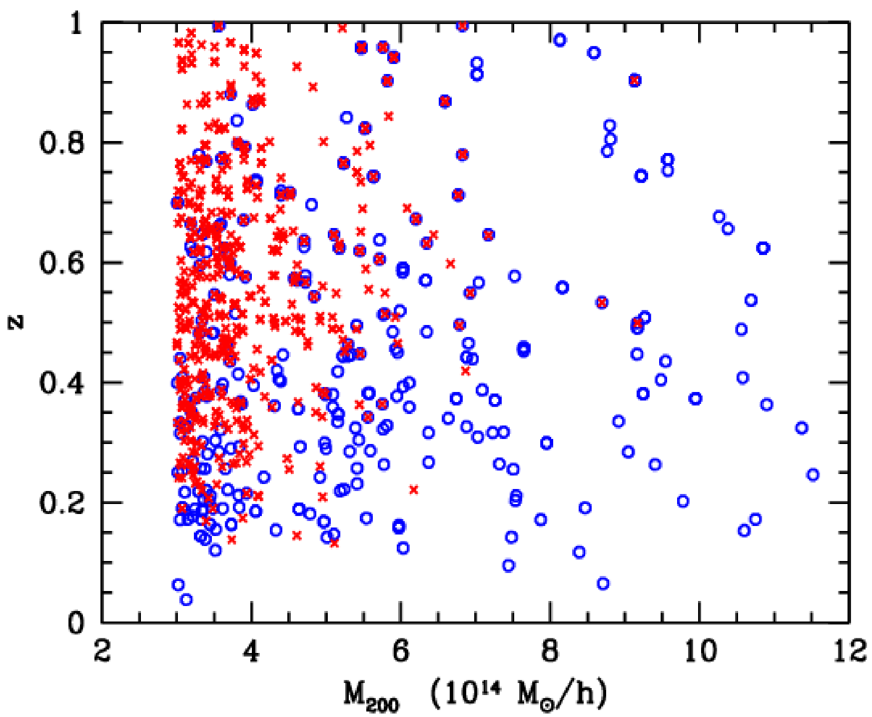


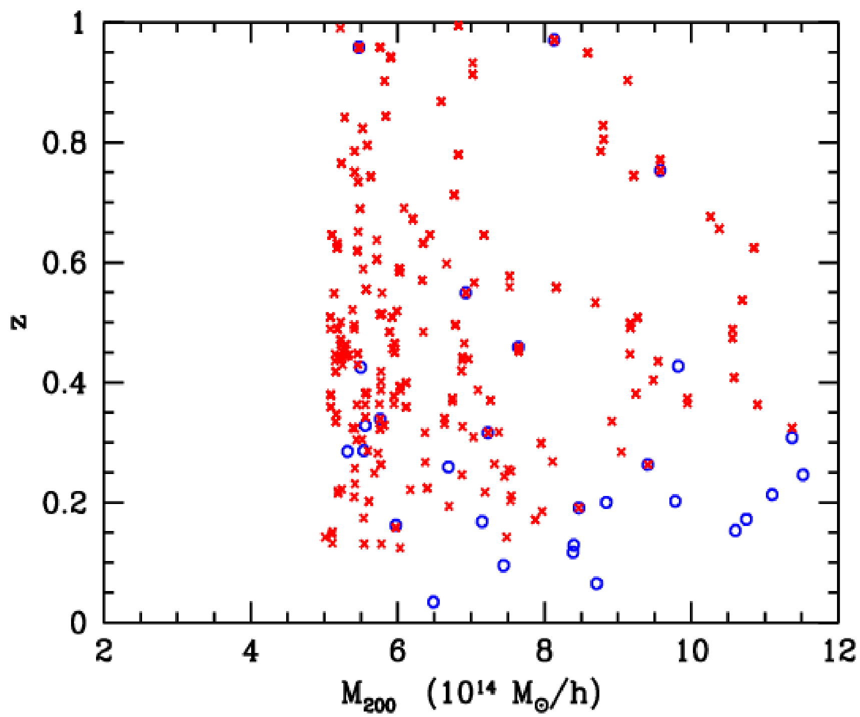
10^0

$\Delta T(353)-\Delta T(217)$ $-100\mu K$ to $+100\mu K$

Planck should detect massive clusters over the whole sky!

(Just searching for local maxima …)



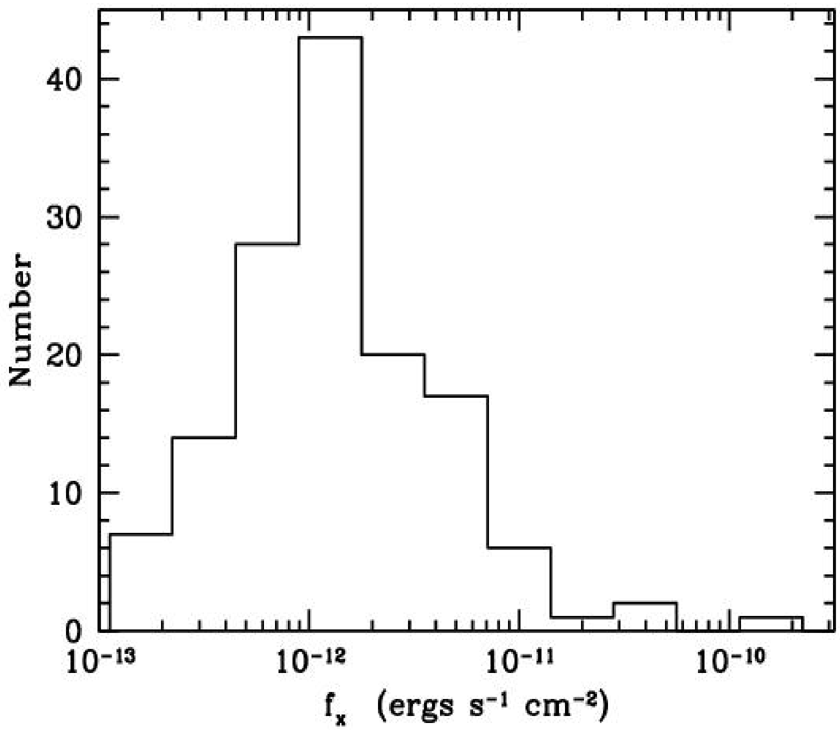


Hi frequency channels, foregrounds under control.

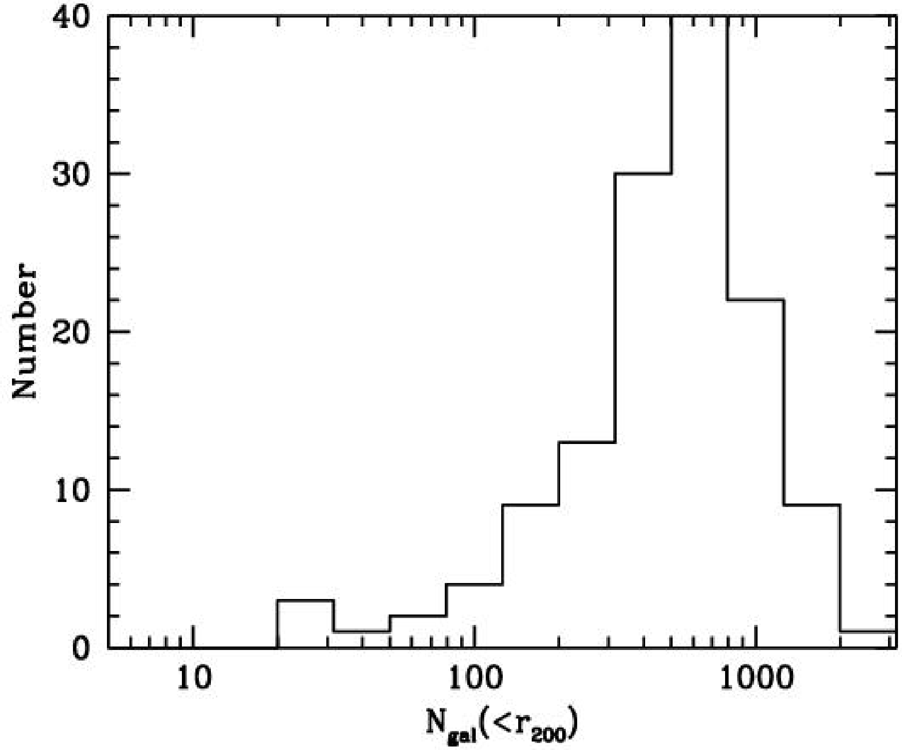
Lower frequency channels, avoid dust and sources.

A great sample for followup!

(All good weak lensing candidates: typically S/N>10)



X-ray flux distribution peaks at 10^{-12} ergs/s/cm^2

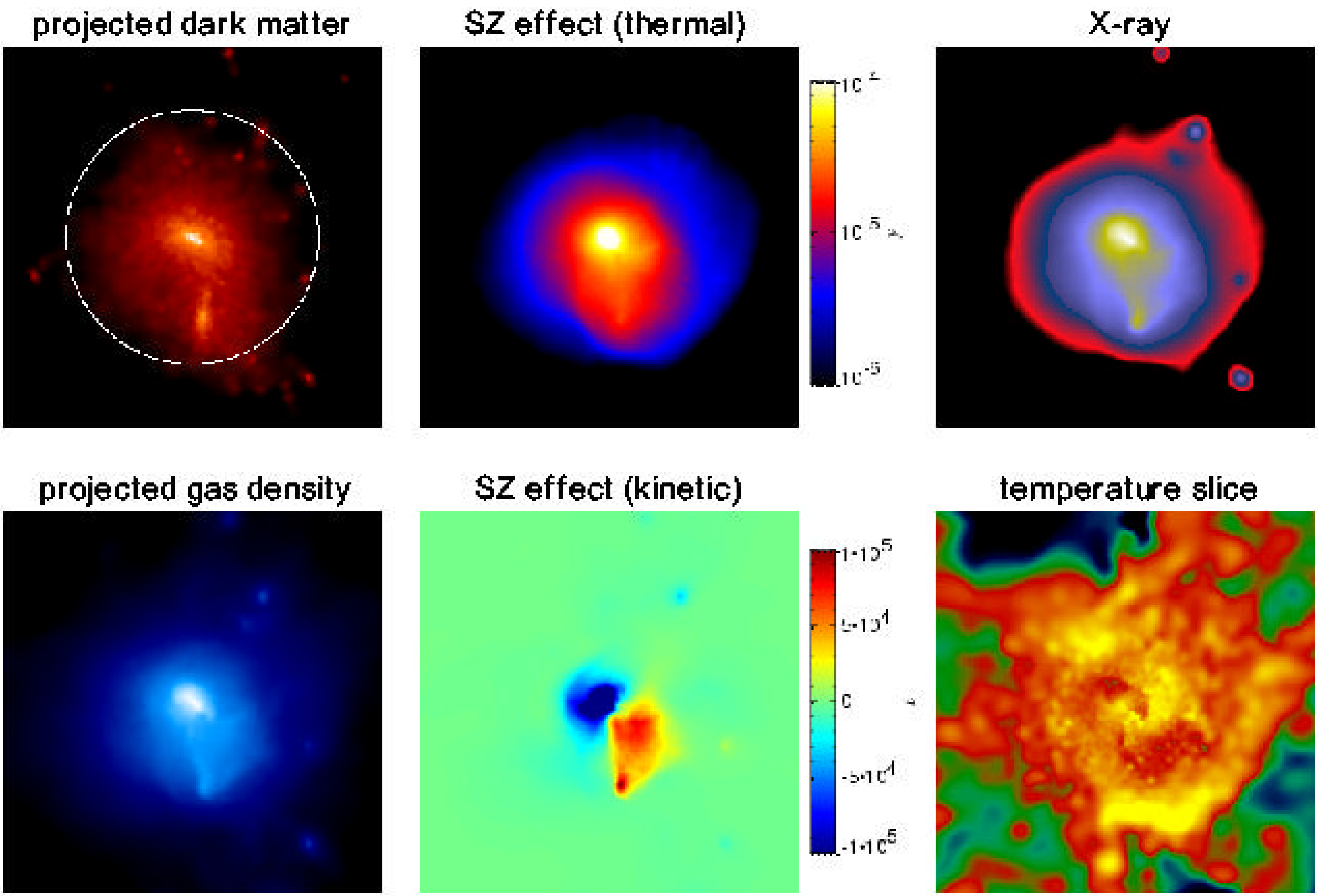


Number of galaxies (R<25) within r_{200}

Number of clusters over 1000 sq. deg.

Combined measurements of X-ray, and thermal & kinetic SZ are powerful tools to study the structure of clusters

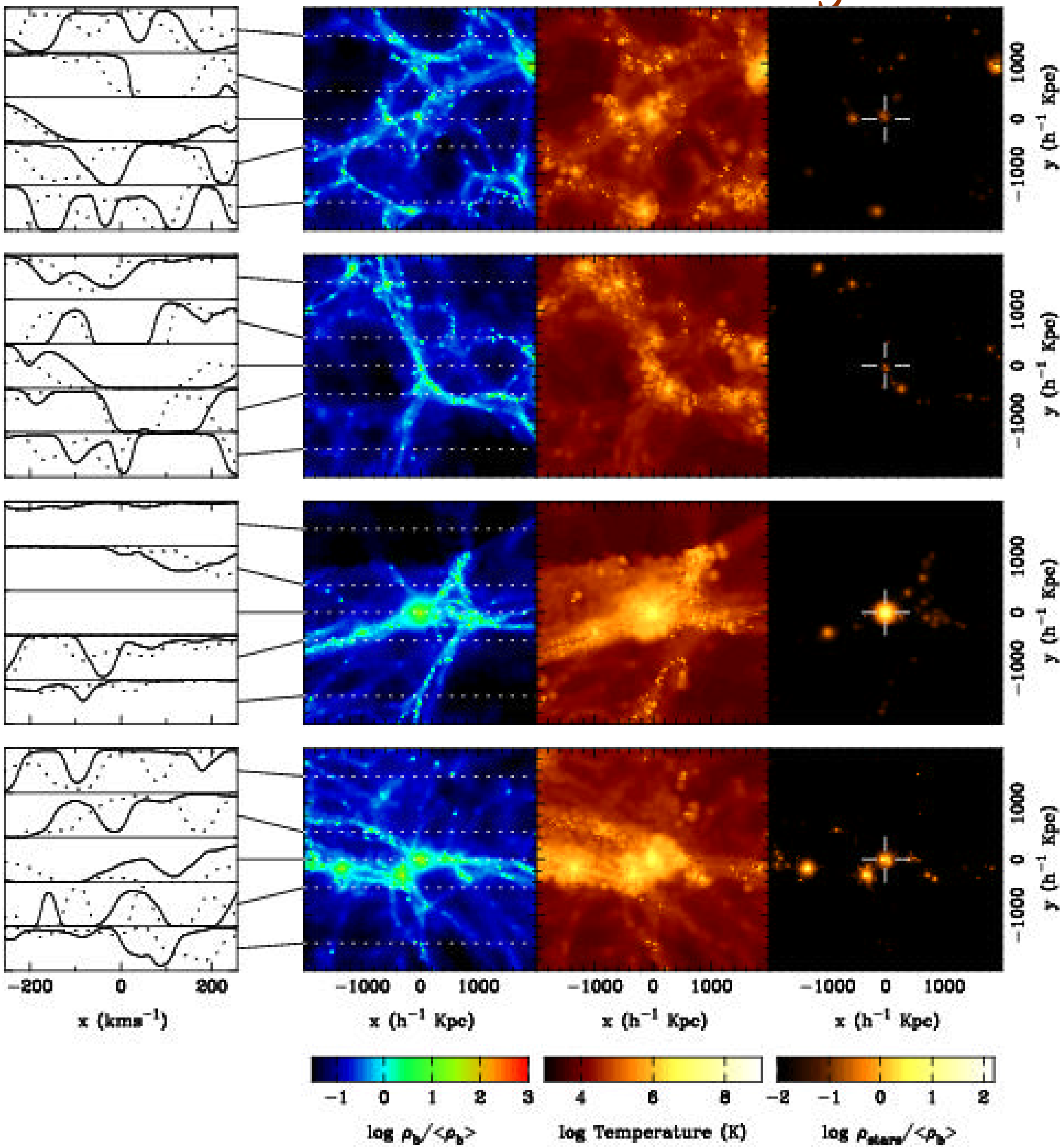
A CLUSTER SEEN IN DIFFERENT WAYS



Adding physics …

- To model galaxy formation or the intergalactic medium we need to include (radiative) cooling for the gas.
- Without feedback there is a cooling "catastrophe".
- Star formation, galactic winds and supernovae return kinetic and thermal energy to the gas
  - All sub-grid physics!
  - Parameterized models.

Small-scale structure: Ly-α forest



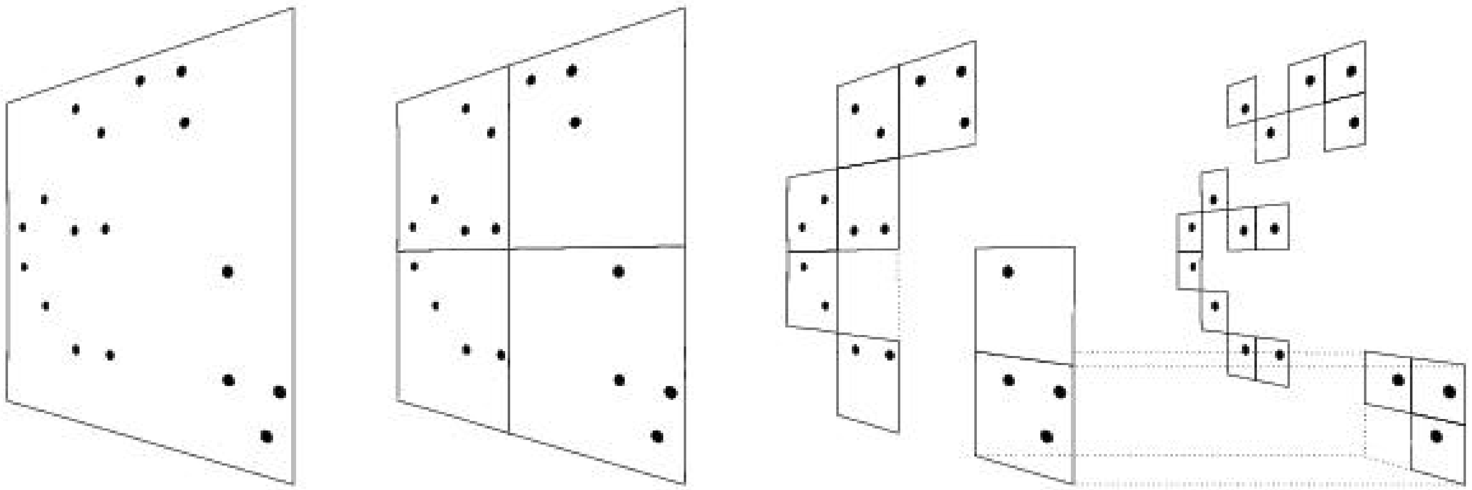
… courtesy R Croft

Conclusions

- Codes to handle only gravity are well understood.
- Memory is the biggest limitation for pure N-body problems.
- Hydro codes are quite advanced, but significant algorithmic improvements are still occurring.
- All important feedback processes are still occurring through parameterized models.
- Radiative transfer is still in its infancy.

STOP

Tree codes



Force on distance collections can be computed using multipole expansion – stored in higher tree nodes.

Oct-tree, kd-tree, hash-tree …